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# HURRICANE MODIFICATION: PROGRESS AND PROSPECTS 1964

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Report to
U. S. Weather Bureau
Advisory Panel Project Stormfury
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N.A.S.A. (Grant NsG 481 to the University of California)
Office of Naval Research (Contract No. 4071 with the
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## I. Introduction, problems and background

The tropical hurricane is one of the most promising frontiers of weather modification. Yet it is a dangerous frontier beset with perils which must be surmounted or avoided if man is to progress toward this important scientific and practical objective. We begin here with the positive features and follow them with warnings of the pitfalls. Most encouraging of all, actual modification experiments have already been carried out on real hurricanes with at least partial success. To our knowledge, these are to date the only experiments performed on an atmospheric phenomenon larger than a single cumulus cloud.

The hurricane or typhoon is one of the worst natural menaces to man. As recently as 1963, a single storm (Flora) took more than 7000 lives and destroyed more than half a billion dollars in property. Thus even a small percentage reduction in destructiveness or improvement in forecasting warrants a large expenditure of effort and funds.

Research over the past decade gives encouragement to these goals. The mature hurricane is a relatively self-contained, at least partially-understood atmospheric circulation. It ranges from 100 to 1000 miles in diameter and lives a lifetime from one to thirty days. Born and bred by tropical oceans, it feeds on the water previously evaporated there into the air, releasing most of this "latent heat" in only a few (1-10) giant cloud towers which form a ring around its characteristic central "eye".

In the Atlantic hurricane, winds above the highly destructive threshold (say 80 knots) are generally restricted to an area of a few tens or hundreds of square miles near the core. Commonly the severe destruction is confined to the path of the wall cloud surrounding the eye of the storm. The Pacific typhoon, the hurricane's larger sister, may exhibit high winds over a much more extensive area, making modification an even more formidable challenge. Storm casualties are 90% due to drowning. The property damage is only in lesser part due to the direct onslaught of the winds upon structures; it is 65-75% caused by inundation of coastal areas from surges of high waters driven by the air motions or occasionally from flash flooding caused by heavy rains. Direct wind damage is roughly proportional to the windspeed squared, and the stress exerted by high winds to move water masses is probably proportional to a somewhat higher power. Thus even a small percentage reduction in windspeed could be of enormous value in saving lives and reducing damage.

The huge energy expenditures in hurricanes might intimidate the hopes of would-be human modifiers. A mature hurricane of moderate strength and size releases as much condensation heat energy in a day as the fusion energy of about 400 hydrogen super-bombs (Yanai, 1964); of this, about 3%, or 12 super-bombs worth, is converted into the energy of winds. In the face of this gargantuan machine, man's puny resources do not allow the brute force, head-on, or trial-and-error approaches. We must seek the Achilles heels or internal instabilities of these monsters. We must further understand these well enough to trigger them in the direction we both desire and predict; that is to say, causal relationships must be postulated and tested. This is the philosophy on which the current hurricane experiments are based and upon which, from them, further progress toward practical modification must proceed.

Do tropical storms possess Achilles heels? Their erratic and unreliable behavior indicates that this is indeed likely. Their frequent sudden alterations in course, intensity and cloud configuration, for no discernible external reason, suggests internal instabilities perhaps set off by very small triggering influences. Paradoxically, however, the very existence of instabilities which gives modification its hope, at the same time constitutes the most serious scientific obstacle facing clear-cut experiments: The natural fluctuations in hurricane behavior are so large and so poorly understood that it will be difficult to establish firmly whether a given change was produced by the human action, or whether the hurricane would have behaved in the observed manner of its own accord. Since hurricanes can develop, collapse, or entirely reverse course in six hours, nothing man can do to one can exceed the naturally occurring fluctuations.

In science, when man's experimentally produced effects are only comparable to the natural "noise" level, we face a real problem. We need "controls" - or alternatively a long, long series of experimental cases. Since individual hurricanes probably differ even more from each other than do individual people or dogs, "identical" pairs of hurricanes cannot be found; furthermore the much smaller storm population suitable for experiment than either the human or canine populations means that a statistically significant repetition of the same experiment might require more than a century!

Related to this scientific problem are the serious political and public relations problems that immediately embroil any attempt at hurricane experimentation. Without severely restrictive precautions, the unreliable behavior of a "modified" storm can launch it into an inhabited region, with resulting furor, lawsuits, and even international accusations. In such cases, it cannot be determined whether the "anomalous" behavior was induced or natural. To make matters worse, the news media frequently take advantage of the naivete of some scientists and the emotional impact of hurricanes on the public to blare forth that man-made hurricane control is on the horizon or here; the citizen then, quite reasonably, wants to know why Hurricane Hepzibah was allowed to destroy his chicken farm.

Hurricane experiments, even at their most modest, cost large fractions of a million dollars, require more than a hundred participants, and at least several specialized aircraft. They can hardly be carried out in secret, and in most countries public accountability for such large expenditures is required. And these expenditures cannot at present be justified by any honest promises of practical results. The investment must be made as an essential background, absolutely necessary for future benefits, but not in themselves guaranteeing any direct road to these benefits - which might, in fact, never be forthcoming. The politicians and the public must be educated with the help of a responsible press to recognize this. Meteorologists must have enough self-discipline not to exploit or claim credit for the innate erratic behavior of the hurricane. Without these restraints, the potential benefit to science and to humanity will be sacrificed at this beginning stage, with respectable scientists shunning all connection with modification efforts.

The thesis of this report is that while practical hurricane control is a dream which may be five or fifty years away (or even impossible), modification experiments are a reality whose potential is just starting to be explored. They have been begun; they must be increased and greatly extended as a background if practical mitigation of storm hazards is to be achieved. Even without this hope, such experiments can provide accelerated insights into hurricane behavior which years of straight measurement on natural storms might not yield. Moreover, they can lead the science of meteorology into the category of experimental sciences like physics, where the effects of specified and pre-determined causes may be studied quantitatively in a real large-scale atmospheric laboratory.

It is often debated whether hurricane experimentation can be most fruitfully undertaken in the formation or in the mature stages of the storm. Presently, the evidence favors the latter, if a choice must be made due to limited manpower and resources. The reasons are two-fold: Firstly, the causes of hurricane formation are very poorly understood (Yanai, 1964) which would render a causal linkage difficult to establish or its interruption dubious either to effect or to prove; and Secondly, there may be as many as fifteen or twenty apparently identical incipient storms from which only one will make hurricane. It will be a long time before man can afford to operate on every tropical storm that might reach hurricane force.

On the other hand, the annual number of full hurricanes in any ocean never exhausts the alphabet to name them and most of these remain relatively harmlessly at sea. In the mature stage, the mechanisms and operation of the storm engine is fairly well documented and understood (for example, Malkus and Riehl, 1960; Riehl, 1963; Yanai, 1964, loc.cit.). Therefore, it has become possible to formulate and test hypotheses on how their delicate balances might be upset. The current series of hurricane experiments are based on one such hypothesis regarding the mature storm; it depends upon modifying (by seeding) the clouds in the storm core. This class of experiment will be discussed next in Section II. In Section III we will then proceed to explore how knowledge gained from these and their sequels might be used to evolve other experiments on the mature storm and in incipient storms. Finally, in Section IV we will consider entirely different classes of experiments which might be contemplated.

## II. Hurricane experiments involving cloud modification

### A. Techniques and early history

Most cloud modification techniques involve converting a super-cooled water cloud into one composed of ice or snow, using either dry ice or silver iodide. In the free atmosphere, water turns to ice "spontaneously" only when the air is colder than -40°C. Between 0 to -40°C, freezing nuclei are required, and these are often either insufficient or not active enough to convert most of the cloud water into ice when the cloud is warmer than about -20°C. Seeding normally means putting ice or ice-like particles into the cloud, so its conversion will take place at higher temperatures, that is between 0°C to -20°C. It is not yet understood whether the seeding causes direct sublimation onto the nuclei and evaporation of the pre-existing water, or whether the nuclei cause the existing drops to freeze; in any case it appears that a water drop cloud becomes one filled with snow crystals, and that latent heat of fusion is released.

Dry ice creates ice crystals by chilling the adjacent air below -40°C. Silver iodide acts as a freezing nucleus apparently because its crystal structure resembles that of ice. It is cheaper than dry ice, and from it at least two orders of magnitude more ice crystals are obtained per gm ($10^{14}$ - $10^{16}$ compared to $10^{12}$ for dry ice, see Braham and Neil, 1958). But dry ice falls through a cloud and becomes active right at $0^{o}C$. Silver iodide only begins to be active at about $-4^{o}C$, decays after exposure to sunlight, and special vehicles are necessary to get it to fall vertically through a cloud, as we shall see.

Recently, it has been suggested (Fukuta, 1963) that the organic compound metaldehyde would be a most promising seeding material, since it is both cheap and becomes active near freezing; so far, however, only laboratory trials have been made. Above-freezing cloud seeding has been attempted with both water drops and pulverized salt to increase rainfall by assisting the drop growth by aggregation or coalescence; to date it has not been explored whether or not these approaches would have any value in hurricane modification.

Cloud modification was initiated by Vincent Schaefer eighteen years ago (Schaefer, 1946). He first found that dry ice worked to transform supercooled stratus clouds into snow. The use of silver iodide was discovered shortly afterward by his associate Vonnegut (1947). Inspired by Nobel Prize winner I. Langmuir, Schaefer, Vonnegut and their colleagues at the General Electric Company in the United States made numerous pioneering calculations and experiments with cloud seeding. It is not surprising that they thought of using their discovery to try to mitigate hurricanes. In fact, their Project Cirrus performed the world's first hurricane experiment in 1947 (Schaefer, 1953).

This was strictly an "exploratory" experiment, as no quantitative or even qualitatively testable predictions could be made in advance regarding expected results of the seeding. In those days, tropical storm research was so lacking that the existence or amount of supercooled water in a hurricane could not even be guessed. It was planned to seed a young storm just "to see what happened" in the hope that the cumulonimbus towers might be dissipated before they became organized into a well-defined storm. It could equally well have been argued at the time that the fusion heat release might intensify the circulation, or that no consequences would be detectable.

Actually, a mature hurricane was seeded in a location off the U. S. Florida Coast, with a total of 180 lbs of dry ice. The storm had a 30-mile diameter eye, with wall cloud and rainband towers up to an estimated 60,000 ft. The seeding, however, missed these and was performed first along a 110-mile outward track starting some distance from the center. A load of 80 lbs of dry ice was dispersed along this path. The observers report (Schaefer, 1953, loc.cit.) that stratus clouds were subsequently converted to snow over an area of about 300 square miles. In addition, two

50-lb loads of dry ice were dropped into a single large cumulus at the outer end of the track, but no reports are available regarding the outcome.

Unfortunately neither of the two Project Cirrus aircraft was equipped to monitor the dynamical or structural changes in the hurricane, or to make systematic "before and after" pictures of cloud patterns. The only other index for judging the effect of the operation was the behavior of the hurricane during the succeeding day and a half. Therefore the experiment became the subject of an acid scientific controversy. During the twelve-hour period centered on the time of seeding, the storm - while moving eastward - apparently weakened and there was some evidence that more than one center may have existed (Mook et al., 1957). Of greater interest, however, was the fact that during this period the vortex changed course and began moving slowly westward. Ultimately it moved inland near Savannah, Georgia, about 30 hours after the seeding.

The fact that large-scale circulations surrounding the hurricane were already changing, prior to the seeding, in a manner which would probably have blocked the northeastward path of the storm, further compromised attempts to evaluate the effect of seeding, since only synoptic-scale observations were available to judge the changes. The damage to the Georgia coast led to an unpleasant lawsuit against the experimentors' organization, teaching the lesson that rigid precautions must be taken to tamper only with storms which cannot conceivably strike land within a reasonable time thereafter. Restrictive ground rules of this type have been drawn up for the current experiments; these limit the number of accessible Atlantic storms to about 1-2 per year, unfortunately.

This experience also showed clearly that unless some means could be found to monitor the changes occurring in hurricane structure, intensity and movement - in detail for several hours before and after seeding - it would remain impossible to evaluate objectively the results of <u>any</u> experiment. It further demonstrated that knowledge of hurricane structure and mechanisms had to be developed along certain very specific lines: our understanding of the machinery had to be increased to the point where we could postulate causal relationships and <u>predict the consequences</u> of trying to interrupt these at a given link. If cloud seeding was to be the means of experiment, we had to learn the relation between cloud dynamics and storm dynamics, to see how altering one might alter the other subsequently. This motivated, at least in part, the founding of the U.S.Weather Bureau's National Hurricane Research Project, and constitutes the foundation of its off-spring, Project Stormfury, which is carrying out the current hurricane experiments.

B. Hurricane research and the role of clouds.

In the summer of 1956, the U. S. Weather Bureau, in cooperation with the Air Force and Navy and leading university scientists, launched the National Hurricane Research Project. Its mission was detailed investigation of the hurricane core by means of specially instrumented aircraft, supplemented by strengthening the West Indies rawinsonde network. Hurricane flights were usually conducted at three altitudes,one near cloud base, one in the middle troposphere (10 - 17,000 ft) and one at the outflow level (about 35,000 ft). The aircraft were equipped to record winds, heights of pressure surfaces, temperature, humidity and cloud water content every few seconds on punched cards (now magnetic tapes). These are fed directly into a high-speed computer, bypassing the enormous labor in reducing airborne measurements to a form useful to the meteorologist. The data are printed out in coordinates relative to the moving storm center as well as in geographic latitude and longitude. In addition, the aircraft have been equipped with radars and cameras for cloud study and other special instruments, such as a gust probe for turbulence measurements. The present aircraft fleet and its instrumentation are described in a manual by Reber and Friedman (1964); they will be mentioned further here later on.

About a dozen full Atlantic hurricanes and one sub-hurricane tropical storm have been penetrated and successful results analyzed and written up to date. An excellent review has been published by Riehl (1963a). The specially interested reader is referred to six important publications on a single hurricane, Daisy 1958, which are the contents of the Special Bibliography herewith. Probed on three successive days, aspects of Daisy ranging from cloud structure to momentum and energy budgets are described quantitatively; despite her harmless career, she has become the world's most studied storm.

As a result of the Weather Bureau Project, the hurricane is undoubtedly the most intimately exposed and best understood class of atmospheric circulations. The working of its machinery can be described quantitatively and fairly effective mathematical-physical models are being constructed from and tested by these observations. Most important for our purposes, the vitally important role of clouds has been revealed; it has been documented how huge cumulonimbus towers serve as both the combustion cylinders and fuel pump in the hurricane heat engine.

The crux of a hurricane is its warm central core. Most tropical disturbances live and die with a cold interior, which precludes their operating as a heat engine to generate strong winds. The rarity of hurricane formation in the tropics is explained by the great difficulty in establishing the warm center. The structure and function of the warm core is illustrated in Fig. 1. The crucial relationship is the proportionality between pressure changes or gradients along the storm radius and corresponding changes in temperature of the air columns, as given by the so-called hydrostatic relationship, a basic law of the atmosphere.

The pressure along the top of a hurricane (at 50,000 ft, say) has been found not to vary. Within the storm, horizontal pressure variations drive the winds: these are governed by the temperature structure. Warm air columns are less dense than cold columns and therefore exert less pressure at the earth's surface. To lower the central surface pressure to about 980 mb, corresponding to a moderate hurricane, the core must be 5 - 6°C warmer than the surroundings; to lower it to 940 mb, for a severe hurricane, the hydrostatic law tells us that the central regions must be warmed 8-10°C over the exterior.[1]

It is the sharp drop in pressure toward the center, or "pressure head" directed inward that maintains the mass inflow at low levels (Fig. 1b) and therefore cranks up the vicious rotating winds of the hurricane. As the air is drawn inward toward the center, the earth's rotation causes it to wind up in a cyclonic (counterclockwise in the Northern Hemisphere) spiral - like the whirling skater who draws in her extended arms; she must then revolve faster to conserve angular momentum. While some of the hurricane's angular momentum is lost to the rough ocean, this only means that a warmer core is needed to drive the air against this frictional effect.

Aloft, quite a different picture prevails, again governed by the warm core. Warm columns are more expanded than cooler ones, and thus as we go upwards their pressure decreases more slowly.

[1]Note that the calm "eye" is often warmer still, due to compressional heating of the air slowly sinking there. The "eye", however, probably does not contribute usefully to wind production, but only the warmth of the cloud wall around the eye, where the inflowing air actually ascends.

In the upper troposphere, the warm core exhibits higher pressure than the surroundings and there is a "pressure head" directed outwards, maintaining the hurricane outflow. This outflow is vital to the storm's existence; it gets rid of the inflowing mass and released heat, which otherwise would shortly kill the storm. Because of the previous loss of angular momentum at low levels, the absolute rotation of the outflowing air is less than that of the inflow so, relative to the earth, it becomes an anticyclonic (clockwise in the Northern Hemisphere) rotation beyond radii of 50-100 miles (Fig. 1c).

But how is the warm core maintained and why is it so hard to make one? Clearly it is established by the condensation of water vapor into rain as the inflowing air rises - that is, by the latent heat of condensation. But these processes oppose. Lifting cools air by expansion and thus the condensation must occur in a very special way to make a net balance toward increasing or even maintained warmth. Fig. 1a might be interpreted to imply a gradual, uniform ascent through the storm interior, but this would lead to cooling and cannot be what occurs. One of the most important discoveries of the Hurricane Project is that nearly all the ascent in the storm core takes place in very narrow channels - these channels are the giant cumulonimbus clouds called "hot towers" which occupy an average of about 4% of the mature hurricane area, becoming denser toward the center and reaching maximum concentration in the eye wall. These clouds compose the famous spiral "rain bands" observed on radar (Fig. 2). Nowadays extensive radar, photographic and aircraft studies of their distribution and structure are available (e.g. Malkus, Ronne and Chaffee, 1961; Gentry, 1964). The role of hot towers in the storm's transports and energy budgets has been documented for Hurricane Daisy, 1958 (Riehl and Malkus, 1961).

To create the full-blown hurricane warm core, one further essential ingredient is required, and that is an oceanic heat source in the storm region itself. The air entering in the inflow must be exposed to the ocean and able to pick up enough extra warmth from it, so that when it ascends its heat content is much higher than that of ordinary tropical air; this point is illustrated in Fig. 3. And when the warmed air ascends, it must ascend high and fast - the higher the released condensation heat gets before flowing out, the more effective it is in lowering the surface pressure; computations show that two-thirds of the pressure drop is due to warming above 400 mb (about 25,000 ft).

To get this kind of rapid channelled ascent of surface air, special giant clouds are necessary. Cumulus studies have shown (for example, Malkus and Williams, 1963) that small clouds lose too much of their precious heat content by mixing with the surroundings, and perish in the low and mid-troposphere. A minimum diameter is required for penetration and heat transport of "undiluted" subcloud air to great heights.

In summary, a gradual mass circulation, or small cumuli, or towers unconcentrated toward the center, would permit the usual victory of cooling over warming in ascent, so that a cold core, non-hurricane disturbance is the most that could result. Highly concentrated, large diameter "hot towers" in the eye wall, together with an oceanic heat source, are necessary to provide the warm core, and thus the extreme pressure drops needed to drive hurricane winds. These occur in specifiable proportion, and numerical relationships between wind strength, warmth of core, hot towers, and oceanic heat source are now available and tested (Malkus and Riehl, 1960; Riehl and Malkus, 1961; Riehl, 1963).

Thus the linkages between cloud and storm circulation are sufficiently understood to formulate hypotheses on how man might try to break the chain and real atmospheric experiments can be designed to test these. The Stormfury project and its current experiments are based on one such hypothesis.

C. The physical basis of the current hurricane experiments

The Stormfury hypothesis, beginning with observations (Simpson, 1963) suggesting that supercooled water abounds in hurricane cloud towers, proposes that silver iodide seeding can release heat of fusion in the eye wall, the site of maximum pressure fall toward the center. Making these hot towers hotter would further lower the surface pressure in its region of steepest descent, reducing and displacing outward the maximum radial pressure gradient. Normally, the inward-directed pressure gradient force is just enough marginally to balance the centrifugal force on the air whirling around the storm center. By reducing the pressure gradient, the balance could be upset so that the centrifugal forces dominate, leading to outward displacement of the air. This would be particularly effective if an unstable equilibrium prevailed initially. Several workers (see Yanai, 1964, loc.cit.) have suggested that "inertial instability" may occur near the centers of some hurricanes. Simplified, this means that the velocity distribution is such that if air is given a push outward, forces will be brought into play that will accelerate it still farther outward, even into rising pressure.

Thus the seeding could, by upsetting a marginal balance of forces, induce an outward migration of the wall cloud and thus increase the radius at which the ascent of the inflowing air occurs - and this is the crux of the experiment. For the difference between a hurricane and a mere "tropical storm" lies not in the total condensation energy released, but in the concentration of the release near the center (Riehl and Gentry, 1958). Dynamically, it is the momentum production of the last few miles penetrated by the inflow that leads to extreme winds. Thus an increase in the radius at which the ascent takes place should result in a decrease of the maximum windspeed.

Although there are many assumptions and untested links in this chain of reasoning, the magnitude of each effect can be estimated in advance, up to and including the reduction in the radial pressure gradient. Thus measurements can test these predictions and the design of an experiment becomes meaningful, provided that the operational difficulties can be overcome, which is another class of problem.

The hypothesis is illustrated quantitatively in Figs. 4-6. Fig. 4 shows the schematic hurricane cloud model, synthesized from the observations discussed earlier. Above, we look down on the rainbands, noting that the most active part of the eye wall is usually found in the right front quadrant, where the radial motion is frequently weakly outward at all levels (cf. Fig. 1b). A major fraction of the "hot tower" ascent is concentrated in this one chimney area, particularly in well-developed steady hurricanes. This is illustrated in the lower part of Fig. 4, a schematic cross section through the storm.

Fig. 5 shows the modified temperature structure inside the wall chimney, calculated to prevail after seeding. This calculation (by Simpson, Ahrens and Decker, 1963) first assumes the freezing of 1 gm per $m^3$ supercooled liquid water, uniformly distributed between the freezing level (500 mb) and the top of the storm (150 mb). This contributes about half of the roughly $2^{o}C$ temperature increase; the other half comes from the excess of the heat of sublimation over that of condensation as the cloud towers rise, now turning water vapor into ice instead of liquid water as previously. Also assumed is an undistrubed level pressure surface at 150 mb and the export in the outflow aloft of all ice crystals formed.

The pressure drop can be computed directly from this new temperature sounding using the hydrostatic relation. It amounts to 6-7 mb, or a drop of a little over 200 ft in D-value, which means that a pressure surface descends that far. This is illustrated in Fig. 6, from which we compute that the steepest pressure gradient (here between radial distances of 10-20 miles) is reduced 15-20% and is displaced outward by about 10 miles. How much or for how long this should reduce the windspeed cannot be predicted quantitatively at this stage of our knowledge. We do not know how or how soon the hurricane forces will readjust to this shock, nor can the amount of response to an outward push be predicted yet from the theories of inertial instability, even if it is established. Since some specific consequences are predicted, we can perhaps learn most about the others by carrying out the experiment and measuring what in fact happens to the storm.

D. The Stormfury experiment design and project organization

Two factors in addition to the Hurricane Project's capability made this experiment operationally realizable. The first was the invention of pyrotechnic silver iodide generators which could be dropped like bombs from aircraft into selected clouds along a chosen course. These were designed and developed by Dr. Pierre St. Amand of the U. S. Naval Ordnance Test Station. They contain silver iodate with a nitrasol binder. The compound burns at a temperature of 1700°C and yields, per gm of silver iodide, about $10^{14}$ crystals ranging from 0.1 to 1.0 microns in size (St. Amand and Henderson, 1962).

A number of these units are dropped in the wall cloud, as shown in Fig. 7, along a radius such that the furious cyclonic winds carry a dense sheet of silver iodide smoke counterclockwise around the storm center; it should make a complete circuit in 1-2 hours if not rained out previously or ejected aloft in the outflow.

The second vital enabling factor was the ability of the U.S. Navy to coordinate, with radar, the precision maneuvering of ten specially equipped aircraft. To effect this safely and in synchronization in the murky and turbulent conditions of the full hurricane is no mean achievement and it is noteworthy that, operationally speaking, the experiment has been a success on all four times attempted to date.

The Hurricane Project aircraft are used in the experiment for the essential function of monitoring: that is, for making detailed measurements of storm core structure for a period of 2½ hours before seeding and for an additional 2½ hours after seeding. The Weather Bureau's monitoring aircraft are three, with an occasional fourth.

Two are instrumented DC-6's flying at 7000 and 18,000 ft along the successive legs labelled A, B, C etc. in Fig. 7. This entire track is flown before seeding, and the vital A, B, C, D, E sector again after seeding. Winds, pressures, temperatures, cloud water, freezing nuclei counts and cloud structure by radar are the major measurements recorded. A similarly instrumented B-57 is operated at 40,000 ft along an almost identical track. At low levels a B-26 often performs special cloud and rainband studies. The seeding is done by a Navy A3B (with another as back-up). Additional important monitoring is provided by three Navy aircraft, a WC-121 super-constellation radar plane which goes back and forth across the eye wall making frequent dropsondes to obtain eye soundings and the central pressure of the storm as a function of time and two high-flying photographic planes to examine the cloud changes from above. Last, but by no means least, an additional WC-121 is used as "Command Plane" to direct all the others on their courses and to correct them when they get off track. This direction is done by watching all the aircraft on radar and guiding them relative to the radar eye of the storm. When all radars are working well, each aircraft need never be more than 1-2 miles off course and the DC-6's can be vertically synchronized within a minute or two.

It is clear that such a massive operation is too ambitious, requires too much manpower, expense and facilities, for any one research organization or even one government agency. Hence Project

Stormfury was organized as an Interagency effort between the U. S. Navy and Weather Bureau, with some of its support provided by the National Science Foundation. At the time of organization, very special ground rules were drawn up concerning what storms could safely be experimented on; none can be used that could strike a land mass within 36 hours after seeding. Aircraft fuel limitations further preclude storms farther than 500 miles from base. These restrictions mean that only 1-2 Atlantic storms per season will on the average meet the experimental conditions. Nevertheless, since its inception in 1960, Project Stormfury has carried out the experiment on two hurricanes, twice each.

E. Setting of the Stormfury experiment on Hurricane Beulah, 1963.

The first Stormfury experiments were run on Hurricane Esther, September 16 and 17, 1961. The results have been written up in detail and published elsewhere (Simpson et al., 1963, loc.cit.) and will later be summarized here, in comparison with the Beulah case. Only the preliminary results from Beulah have been published so far (Simpson and Malkus, 1963).

Hurricane Beulah first made her presence known on August 19, 1963 as she emerged from the vast unmonitored tropical Atlantic east of the Lesser Antilles into areas which could be reached by reconnaissance aircraft. As she marched westward from her birthplace no weather satellite was in an orbit which could observe the developments.

Fig. 8 shows the storm track and location at the times of seeding on August 23 and 24. On August 23 the storm was still immature and unsteady, and the eye wall was an open semicircle of cloud which was changing position rapidly. A sudden shift occurred just before seeding with the result that the silver iodide was dropped in an open almost cloud-free portion and probably could not have entered the tall towers during the 2½ hour monitoring period after seeding. We will thus concentrate on the 24th when the experimental objectives were achieved.

Fig. 9 shows the chronology of development and decay during the time Beulah could be reached by aircraft, including the period of intensive monitoring associated with the seeding experiment. The change in the pattern of intensification at the time of seeding is especially striking, with a more than 30-knot drop in maximum windspeed and a 15-mb rise in central pressure following the second seeding. However, one is no more justified in assuming <u>a priori</u> that the injection of silver iodide was directly responsible for these changes than one is in concluding that the course of the 1947 hurricane resulted from the application of 180 pounds of dry ice by Project Cirrus. Nor conversely, can it be assumed that there was no connection.

From Fig. 8, it is notable though unfortunate that at the time of seeding Beulah was approaching the point of recurvature, moving slowly northward. After a period of rapid deepening for several days before the seeding, it filled progressively thereafter. The 200 mb circulation reveals that on August 23-24 Beulah was gradually approaching a trough in the upper troposphere, a situation which sometimes reduces the efficiency of hurricane outflow circulations and the export of heat from the storm center. This influence, in addition to the climatological fact that hurricanes tend to reach maturity before recurvature and to decay as they move poleward of about $25^{\circ}$ to $30^{\circ}$ Latitude, has to be considered in appraising the results of this experiment.

However, considering the logistic problems in mounting aircraft support for such an operation, the experimenter rarely has the opportunity to be critically selective in choosing a storm specimen in regard to its direction and speed of movement. Nevertheless, Beulah was very advantageously situated with respect to the base of operations in Puerto Rico. On both days it had full hurricane force winds and a typical circularity to its vortex. On the 24th, it had a well-defined steady eye wall and spiral rainbands before seeding. Moreover, the position, size and intensity were comparable to those of Esther during the seeding experiment in September, 1961.

In view of the uncertainty in the large-scale event chains, we evaluate and compare the experimental results on the basis of shorter period precision measurements of variations in circulation and cloud patterns before and after seeding.

F. Results of August 24, 1963, seeding experiment on Hurricane Beulah

At 1611 GCT on August 24, the Navy A3B seeding plane dropped about 750 lbs of silver iodide into the eye wall of Hurricane Beulah, along a track from 15 to 40 miles from the center, like that shown in Fig. 7. Both seeding and monitoring operations proceeded according to plan.

A striking contrast is provided by the "before and after" pictures of cloud structure, shown in Fig. 10. These composites were derived from an RDR X-band radar mounted in the tails of the two DC-6's so that the antennae rotate in a vertical plane normal to the aircraft heading. The scope gives a vertical (RHI) cross section normal to the aircraft, so that cloud height, size and distance away are easily determined and the cloud is then plotted relative to the flight path. The maps of Fig. 10 are put together from the complete monitoring tracks of both DC-6 aircraft.

Before seeding, the cloud pattern was steady in position, and Fig. 10a was easily composited. Some pulsation in tower top heights with about 30 min period was observed where dotted high towers are shown just outside the eye wall and in the main rainband to the north of center. The seeding location (solid east-west line) clearly released the silver iodide just upwind of the most active portion of the wall cloud. Confirming this are the freezing nuclei counts (Fig. 11); large increases occurred when sampling was done in active convective cells or in the edge of the eye. The cases of little change occurred in areas of stratiform cloudiness.

After seeding, the cloud patterns show a striking change (Fig. 10b). The eye wall appeared to dissipate and reform at a 10-mile greater radius, where the inner pulsating towers were found before seeding. The major northerly rainband also moved outward and its towers grew markedly higher. The cloud patterns were changing rapidly during the 2½ hour post-seeding monitoring period, so that the track of the aircraft (Fig. 7) should be kept in mind while examining Fig. 10b.

The change in cloud distribution suggests that the mean radius of the ascending air was displaced outward following seeding, consistent with the Stormfury hypothesis. However, in deciding whether this is causally connected to the seeding, we are handicapped in knowing next to nothing about the natural fluctuations of cloud patterns in hurricanes. We must thus proceed to examine the monitored storm circulation and dynamics, to determine whether measurable changes occurred and, if so, whether these are also consistent with the hypothesis.

Fig. 12 compares the D-value (height of pressure surface above that in standard atmosphere) profiles before and after seeding on August 24 for radials A, D, E and for the rear quadrant ("in" versus "out" legs, see Fig. 7). For A, the values after seeding were obtained within 20 minutes of seeding time whereas those for the rear quadrant compare values at entry time with those at exit time and represent an interval of more than 5 hours. The slope of these curves is directly proportional to the pressure gradient force. Along each radial, we see that the maximum slope migrated outward and was reduced. The average reduction in pressure in the sector from 10 to 40 miles from the center was 16%, in good agreement with the predictions of the hypothesis.

Figs. 13 and 14 show the variations in wind speed for two of these radials (the other two, not shown, were very similar). "Before" and "after" cloud cross sections from the RDR are displayed above and below. On all sections, the wind maximum lowered and migrated to a greater distance from the center. The largest change occurred in the rear quadrants; there the comparison involves the greatest elapsed time. The average reduction in windspeed is 14% and the outward migration of the maximum ranged from 4 to 10 miles, averaging a little above 6 miles.

Necessarily incomplete calculations suggest that the kinetic energy accumulation rate decreased after seeding, and that the balance of forces was upset in the direction of outward acceleration in the right front quadrant. All changes are thus consistent with the hypothesis, but they are small in comparison with a high "noise" level. Thus the establishment of a causal relation to the seeding poses a difficult, perhaps insoluble, problem that we consider next.

G. Reproducibility, natural fluctuations and planned hurricane experiments.

The first question in assessing causality is to determine whether given experimental results are reproducible. Hurricane Esther was seeded and monitored in the same manner under quite similar conditions on September 16, 1961[1] (Simpson et al., 1963). The results, with one probable exception, were comparable to those for the Beulah case just presented. The variations in wind speed were of the same sign and approximately the same magnitude.

However, in the Esther case the radar clouds on the 10 cm radar showed a quite spectacular disappearance following seeding. About 20 minutes after the silver iodide generators were dropped, the 10 cm return from the eye wall downstream from the seeding run began to disappear and in the 40 minutes which followed disappeared over a 160$^{\circ}$ sector. Reflectivity was restored one hour after seeding. The 3 cm radar showed a complete eye wall throughout this period.

The difference in reflectivity for 3 and 10 cm radars could have occurred if raindrops were replaced by smaller droplets whose diameters were less than about 300 $\mu$, the critical size for 10 cm reflectivity, or if the bulk of reflective precipitation were converted from quasi-spherical drops into ice crystals. Three-centimeter

[1] Another seeding experiment on Esther was attempted on the following day but failed because the silver iodide generators were dropped in clear air.

radar is able to "see" smaller raindrops and snow which cannot reflect 10 cm energy.

Before accepting the freezing explanation, it is necessary to note that the radar antenna was tilted so that much of the radar energy was returned from cloud layers below the freezing level. Furthermore, the silver iodide crystals should have been carried nearly one-quarter the way around the center 20 minutes after seeding. This point was raised as a major objection against a causal relationship between the radar change and the seeding. However, experiments on individual clouds, to be discussed in the next section, suggest that their updrafts' life history is greatly altered by a whole chain of events initiated by the seeding. It is possible that a series of self-sustaining dynamic changes was set off in the clouds at and near the seeding location, which in due course affected their precipitation structure. This point needs further investigation.

In Beulah, any change in radar reflectivity was much less apparent and the quality of the radar photography was inadequate to resolve the point subsequently.

It might be suggested that several more identical repetitions of this experiment must be made. However, even preliminary studies (by the National Hurricane Project, see Simpson and Malkus, 1964) of natural fluctuations suggest that these are of comparable magnitude to the post-seeding changes observed in Esther and Beulah.

A two-pronged attack on this formidable but inevitable obstacle is planned. The first consists of a greatly intensified hurricane experiment of the same kind, tentatively scheduled for 1965. This will consist of five or six seedings of the same storm, repeated every few hours over the better part of a whole day. If the current Stormfury hypothesis is to bear fruit, results in the direction described here must show up greatly magnified and sustained. The second prong of the attack is described in the next section.

## III. Individual cloud experiments and their implications for hurricane modification.

The Stormfury program is based on a chain of physical reasoning. An alternative to testing the end product in the full hurricane is to examine the links in the hypothesis at each step by theory and experiment, some of which can be performed outside the hurricane context. An advantage of this method is that new avenues to hurricane modification could arise from it. This point is well illustrated by our experiment on single cumulus clouds, undertaken in the summer of 1963.

This series of experiments had the triple purpose of testing the pyrotechnic method of introducing silver iodide into clouds, or examining the effect of such seeding in freezing their supercooled water, and of improving existing mathematical models of cloud behavior. The results have been published in detail elsewhere (Malkus and Simpson, 1964; 1964a).

A total of eleven large cumulus clouds were observed by the Stormfury aircraft. Six were studied as "controls" and five were seeded. The control clouds all died within the normal 15-20 minute life cycle without further growth. Of the five seeded clouds, four were successfully seeded when their tops were in the supercooled temperature range at which silver iodide is effective. These clouds grew spectacularly after seeding, in two phases. The first phase consisted of a 10-20,000 ft vertical growth, which occupied 8-12 minutes. The second phase was a horizontal expansion more than doubling the cloud's diameter in a few minutes. The resulting giant cloud usually persisted for at least an additional half hour.

Each seeded cloud was penetrated by the two DC-6's before seeding and many times thereafter and numerous calculations have been made from these measurements. In addition, the clouds were photographed and studied on radar from the Navy command plane and height versus time plots of their growth were thereby constructed. An example is shown in Figs. 15 and 16.

To establish the causal connection between seeding and cloud explosion, an existing mathematical model of cumulus towers (Levine, 1959; Malkus, 1960) was improved and calibrated with the before-seeding observations. This model predicts the tower ascent rate, temperature and water content as a function of height, given its radius, the conditions at cloud base and an environment sounding. This model and its assumptions are discussed in detail elsewhere (Malkus, Simpson and Andrews, 1964). It was applied successfully to the first (vertical) phase of cloud explosion, confirming that unmodified clouds could not have grown, while conversely, the effects of seeding would readily produce the vertical development observed. Thus the first few links in the Stormfury hypothesis are strengthened.

The most important result for our purposes, however, is that the mathematical model can be applied to hurricane clouds to examine the effects of freezing them, both naturally and artificially. Fig. 17 shows a sample calculation for cloud towers 4 km in diameter under mean hurricane conditions. The profiles of ascent rate and excess temperature for the unmodified, unfrozen cloud is given by the solid curves. It is assumed to retain one-half the liquid water condensed, the remainder falling out as precipitation. This gives it a water content of about 2 gm per $m^3$ at 6 km above cloud base, twice the value used by Simpson et al. (1963) in the original Stormfury calculation, but still consistent with very fragmentary existing measurements (Ackerman, 1964).

The artificially seeded cloud performance is shown by the dashed and x-ed curves; this releases the fusion heat linearly between $-4^{\circ}C$ and $-8^{\circ}C$, following the model. The warming relative to the unfrozen cloud is considerable, and is easily enough to account for the pressure drop required by the Stormfury hypothesis (Malkus and Simpson, 1964a). However, quite a different situation would prevail if hurricane clouds freeze by themselves. The dotted curves show a naturally freezing cloud, which releases its fusion heat linearly between -15$^{\circ}$C and -30$^{\circ}$C. The warming and pressure drop of the seeded relative to the unseeded cloud are now cut in half. The prognosis for the Stormfury experiment thus appears rather more gloomy, if natural hurricane clouds freeze most of their water by -30$^{\circ}$C (about 33,000 ft); whether or not this occurs is entirely unknown at this point.

However, as is so often the case in science, a hypothesis may prove to work for the "wrong" or unanticipated reasons and the Stormfury cumulus experiment suggests this possibility in the case of the Simpson hurricane hypothesis. The model illustrated in Fig. 17 treats only the first phase of post-seeding cumulus cloud explosion. In the second (horizontal expansion) phase, the cloud temperature excess over its environment was observed to double or triple, which could not be explained by fusion heat alone. Furthermore, the supercooled liquid water content in small drop sizes increased despite myriads of ice crystals - this suggests the dynamic invigoration of the entire cloud system. If this type of dynamic invigoration were to follow seeding in hurricane clouds, the warming required by the Stormfury hypothesis could result even if the unmodified clouds freeze naturally (but more slowly). The hurricane Esther radar results are perhaps interpretable in terms of this second phase.

These points can be established by well-directed measurements in future experiments. But it is clearly of highest priority to determine the amount of supercooled water and the role of freezing in the unmodified situation, for upon this the course and prognosis of hurricane modification largely depends. To bring this out clearly: The warm core is the crux of the hurricane engine. Via cloud modification we attempt to alter the warm core. If cloud water remains largely supercooled, and little is frozen in nature, then experiments of the Stormfury type are the most promising, where part of the warm core is intensified by sudden forced freezing. On the other hand, if fusion heat plays an important role in the natural storm, it might be better to prevent its release, if possible.

Fig. 17 brings home this latter suggestion. By preventing the natural fusion used in the model, we bring down the cloud from the dotted to the solid curves, reducing its height by 10,000 ft and cooling it by about $2^{\circ}C$ in its upper portions. If this could actually be achieved and sustained, it would appear that the vital transport of heat to the upper troposphere might be significantly cut down or even eliminated. It will be recalled that the upper portion of the warm core is the vital part in reducing the surface pressure and in driving the furious winds. So far no way of preventing freezing in clouds is known; however, a quantitative modification hypothesis can be evolved on this basis in the hope that such a means might be found.

A new cloud modification technique is under development, however, which might conceivably achieve part of the same purpose. A method of preventing cloud drop growth by coalescence has been proposed and subjected to preliminary test by Weickmann[1]. If the cloud drops were prevented from growing enough to fall out from the rising tower, their weight would load it and inhibit its growth. Our model assumed one-half the condensate fell out; similar calculations are readily undertaken to assess the inhibitory effects of varying fractions of water retention in the tower.

Of course, it is quite possible that the extra load of water carried upward would just supply the cloud with more freezing material aloft, so that the fusion heat would later compensate or overcompensate for the added weight. The point to emphasize is not our present uncertainty regarding the outcome of such an experiment, but rather that techniques are available to try out these hypotheses, both in numerical cloud models and in actual atmospheric experiments on individual cumuli. These coupled with hurricane research in fact offer the most hopeful avenues toward eventual storm modification.

[1] Personal communication. It is a homogeneous nucleation process for the formation of condensation nuclei consisting of $H_2SO_4$.

## IV. Other potential approaches to hurricane modification

### A. Numerical models

The numerical models discussed above were simplified treatments of a single cumulus cloud tower. Many attempts at modeling the whole storm circulation have been tried in the past decade, most of them with little or no success. The reason is only partly explained by the general statement that modeling of any three-dimensional atmospheric process is difficult in the present state of knowledge and of computer capacity. A special difficulty arose in treating the hurricane: when all scales (sizes) of motion were permitted to grow in the models, the cumulus cloud size ran away and completely dominated so that storm-size motions could not be detected. When nature forms a hurricane, then the cumulus and storm-scale motions cooperate, not compete. The storm-scale motion produces convergent low-level inflow which the cumuli feed on to release the heat to drive the storm-scale flow. But as we know, this special interaction requires special circumstances, not fully understood.

This physical idea of cooperation between scales of motion was used by Charney and Eliassen (1964) to develop the foundations for the first "successful" numerical hurricane models. They used balanced-force equations for the large-scale flow and parameterize rather than directly introduce the heating by the clouds: that is they formulate the condensation release in terms of the convergence of moist air at cloud base, which is all assumed to go up in undilute "hot towers" as developed in previous theoretical and observational studies (Malkus and Riehl, 1960; Riehl and Malkus, 1961). Their study thereby brings out the surprising and important point that, in the early stages of the storm, surface friction is a necessary de-stabilizing force, because it provides the flow convergence to feed the clouds. In later high-wind stages, its role as energy dissipator can balance or overbalance this.

The Charney-Eliassen formulation does not tell us why nor even under what external conditions a hurricane will grow; it only tells us that one <u>will</u> grow, of the proper size and time-scale, if the input conditions are properly applied. Nevertheless, their work is a major advance which is being carried further on the high-speed computers by others (for example, Ogura 1964). So far, the vertical structure of the storm is highly oversimplified and the manner and physical mechanism of the cloud's best release is entirely bypassed.

Thus it should be clear that we cannot yet try meaningful "modification" experiments on model hurricanes by changing various input parameters fed to the computer. It is unlikely that this goal can be realized prior to the advent of the new one hundred-times faster computers, and more hurricane research, but it is one worthy of a heavy investment at this time.

B. Possible inhibition of the oceanic heat and moisture source.

As we saw in Section IIB, an oceanic heat source operating within the storm itself is the second essential ingredient to sustain the warm core of a full hurricane. The extra heat source comes three parts in the form of moisture from evaporation to one part direct heating from the warm sea. Both heat inputs are enormously enhanced, by the strong winds, over the normal tropical situation. Could we reduce or prevent the warm core by inhibiting one or both of these heat transfers?

The death of hurricanes when they pass inland surely suggests this hope, if a means of suppressing sea-air transfer could be found. Very effective (90-100%) evaporation suppression has been achieved in rice paddies (Mihara, 1962) using monomolecular films of docosanol with ethylene oxide. However, the film tears and is swept away in winds exceeding a few meters per sec. Teller[1] has described work on films which will endure high winds and waves and could be spread over areas several hundred miles on a side. These would at the same time presumably cut down the wind stress on the water and thus, following the reasoning of Charney and Eliassen (1964, loc.cit.) greatly also reduce the inflow convergence and convective heat release of the developing storm.

Although still in the realm of speculation at present, this would appear a promising channel of research for future modifica-

[1]Personal discussion with one of the writers.

tion experiments, with a major reservation regarding storm movement. Hurricanes usually travel from 100 to 700 miles per day. For this technique they could only be caught in their stationary or very slow-moving phases, which sometimes occur early in their lifetime in the tropics or later at recurvature, but rarely in their march toward a coastal area.

A related line of study involves the role of sea salt in the hurricane. Woodcock (1958) has computed that the observed warming of the subcloud air could be brought about by condensation on salt particles. The high winds raise a cloud of these from the sea in foam and bubbles; they are carried up in the cumulus towers and fall slowly back again in the lower humidity air between clouds. When they re-enter the moister (about 90% relative humidity) air below cloud base, considerable condensation on them can occur, releasing enough heat to account for the warming which occurs. If this role of salt nuclei can be firmly established, artificial changing of their number or hygroscopic property might be considered.

C. Possible alteration of radiative processes in the high troposphere.

Simpson (1964) has proposed another method for altering the balance of forces in hurricanes, related to the Stormfury hypothesis but quite different in technique. This is the possibility of imposing a constraint upon the net outgoing radiation over one sector of the hurricane.

This experiment would seek to disseminate very small plastic bubbles, with high absorptivity to infra-red radiation, in an area near the relative "cusp point" in circulation over a mature storm. This point is usually located to the left of center just above the tropopause. It is a calm area which travels with the hurricane. Therefore materials spread over an area 25 miles square would tend to move with the storm center and diffuse outward very slowly. If so, it may be possible thereby to create an asymmetry of ultimate importance to the hurricane structure and circulation. This is a realizable experiment which might be carried out within a year or two.

In contrast, there are other much more distant, but still interesting, proposals regarding alteration of radiative properties in the high atmosphere. In a recent review article on hurricanes and their possible modification, Riehl (1963a, loc.cit.) has pointed to the importance of a cirrus shield in protecting the air below from radiational heat losses. From satellite radiation measurements, it is shown that air under this upper cloud canopy would warm up by about $1^{o}C$ in 24 hours, relative to the outside air, as a result of this one effect alone. Riehl suggests that this may be important, even decisive, in warm core formation. He emphasizes, however, that sub-hurricane tropical storms have cloud canopies that probably would show similar radiative properties to satellite measurements.

Suggestions have been made that the radiation-protective properties of such canopies could be reduced by scattering special particles, like soot, in the high atmosphere, or even that these high clouds might thereby be dissipated, conceivably preventing storm formation. Certain "danger areas" such as the Gulf of Mexico could be monitored by satellites and the dissipative materials spread by rocket or aircraft when the threatening cirrus shield first appears. Such ideas are sheer speculation at the present time and should not be taken seriously.

Furthermore, since hurricanes and tropical storms are a major vital summer rainfall source for the South Central United States, and for other areas of the world, caution must be exerted against killing all tropical storms, if and when this should loom as a real possibility! It would appear better to try to reduce the hurricane force winds and leave the rest of the storm intact, as do those experiments such as Stormfury which are aimed at the wall cloud and inmost warm core.

## V. Concluding remarks.

Some of the hurricane modification schemes just mentioned sound much like science fiction, and could indeed be that. It might be replied that two decades ago space travel and moon rockets were science fiction. It should be emphasized, in conclusion, that hurricane modification is qualitatively quite a different problem from that of space probing: it is first of all a scientific problem, and only subsequently an engineering problem. For even if man could manipulate energy comparable to that of the storm itself, he still would not <u>know</u> how to direct it to destroy or deflect the hurricane. His first task must be to learn enough about atmospheric physics and dynamics to do this; it is not simply a matter of mounting a technological effort.

Hurricane research and carefully designed hurricane experiments, without immediate practical promise, must be continued and accelerated. A testable physical hypothesis is essential as a basis. Random exploratory experiments are almost sure to be quite useless, not only because of the huge energies involved but because of the erratic behavior and high natural noise level exhibited by the phenomenon. Statistical evaluation alone is not a satisfactory tool to establish causal relations in hurricanes, both because of lack of "control" storms and because of the long series of experiments, perhaps over a century, required for a valid statistical sample.

Physical hypotheses, on the other hand, can be tested at each link in their chain, some outside the hurricane context, where easier operation and better controls are possible. The current Stormfury hypothesis is still hopeful, but even if it is not successful in leading to practical modification, testing it has already added to hurricane knowledge and has suggested other experiments and alternative hypotheses.

For both economic and scientific reasons, the hurricane is today probably the most hopeful avenue of weather modification studies; this avenue must be pursued with a high degree of combined enthusiasm and caution.

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Riehl, H. and J.S.Malkus, 1961: Some aspects of hurricane Daisy, 1958. Tellus, 13, 181-213.

## Titles for Illustrations

Fig. 1. The role of the hurricane warm core (after Riehl, 1963a)

a. Vertical circulation through a hurricane, outline of the main cloud mass, and temperature distribution.

b. Low-level (1000 ft elevation) streamlines in hurricane Donna southeast of Florida in September 1960. The open arrow indicates the direction of hurricane motion.

c. Upper-level (45,000 ft) streamlines in hurricane Donna.

Fig. 2. Distribution of radar echoes (the solid areas are intense echoes, outlined areas are of lesser intensity) for hurricane Daisy on 25 August, 1958, 1800-2300 GCT. The flight path of the observing aircraft (National Hurricane Research Project) at 37,000 ft is shown. Scale is indicated in nautical miles. (Courtesy William Gray, Colorado State University).

Fig. 3. Temperature in degrees Centigrade plotted against the logarithm of pressure (essentially, against height). Dashed line: Structure observed in the mean atmosphere from balloon soundings over the Caribbean in summer. Solid lines: Structure obtained from undilute ascent of trade-wind air and structures required within a moderate and severe hurricane in the heavy cloud mass around the eye of a hurricane. Note that both hurricane soundings

require warming at low levels - extra heat addition from oceanic source - the severe hurricane more than the moderate one. (After Riehl, 1963a).

Fig. 4. Schematized model of cloud structure and distribution in mature hurricane. The primary energy cell (cumulonimbus chimney) is located in the area enclosed by the broken line. (After Simpson, Ahrens and Decker, 1963).

Fig. 5. Vertical structure (sounding, compare with Fig. 3) of air in hurricane periphery (curve A) and unmodified and modified (B and C) air rising in the chimney area of the eye wall. (After Simpson, Ahrens and Decker, 1963).

Fig. 6. Anticipated change in slope of pressure surfaces due to seeding. The slope of these curves is proportional to the pressure gradient force. The abscissa is distance from storm center; the ordinate is D-value, which is the departure in height of a pressure surface from its height in the standard atmosphere. (After Simpson, Ahrens and Decker, 1963).

Fig. 7. Seeding and monitoring patterns for aircraft in the Stormfury experiment. The seeding plane flies outward along A, dropping the silver iodide generators in the region of the circles. The monitoring patterns are shown by the tracks A, B, C etc. These are to be performed before and after seeding. The open arrow indicates the direction of storm motion.

Fig. 8. Hurricane Beulah track 20-28 August 1963 and seeding positions and times (Tango). The aircraft were based at Roosevelt Roads, Puerto Rico.

Fig. 9. Chronology of hurricane Beulah's central pressure (left scale) and maximum windspeed (right scale), August 20-27, 1963. Times of seeding denoted by vertical lines.

Fig. 10. Before and after radar composites of cloud structure in hurricane Beulah, August 24, 1963.

a. Before seeding (seeding time 1611Z or Greenwich) composite, constructed from RDR film made from both DC-6 aircraft flying the monitoring tracks of Fig. 7 between 1350-1611 GCT.

Numbers give heights of echoes in thousands of feet. Dotted echoes are transient or pulsating. Stratus cloud denoted by hatched regions; cirrus by shaded regions. Seeding track shown by solid line. Note that it is just upwind of the tallest towers, so that the sheet of silver iodide smoke was surely carried into the active portion of the eye wall cloud.

b. After seeding composite constructed in the same manner from monitoring tracks flown between 1611-1820 GCT. Cloud structure was changing rapidly during this two-hour period. Towers with solid lines above their height notation are dissipating. Note destruction and outward migration of wall cloud and increased tower heights in first rainband to north of storm center.

Fig. 11. Freezing nuclei counts before and after seeding hurricane Beulah, 24 August 1964. Measurements made with Bigg-Warner cold box, calibrated to give count of 0-4 in clear air. Naturally freezing clouds commonly show counts of about 30-100, while artificially seeded clouds give counts 12,000 or more. These values are hundreds of active nuclei per $m^3$ but relative magnitudes only should be considered. Figures in parenthesis denote the number of minutes before or after (+ or -) seeding that the measurement was made. Arrows show how far the air would have travelled during that interval.

Fig. 12. D-values before and after seeding hurricane Beulah, 24 August, 1963. Compare with Figs. 6 and 7.

Fig. 13. Center: Windspeeds (at 18,000 ft) before and after seeding (along Leg E, see Fig. 7) hurricane Beulah, 24 August, 1963. Above and below: Before and after cloud cross sections along same leg, constructed from RDR radar.

Fig. 14. Center: Windspeeds (at 18,000 ft) before and after seeding (outbound compared to inbound leg, see Fig. 7) hurricane Beulah, 24 August 1963. Above and below: Before and after cloud cross sections along same leg, constructed from RDR radar.

Fig. 15. Development of seeded cloud on August 20, 1963. Top left: Time of seeding. Top right: Just before maximum vertical growth, 9 minutes later. Bottom left: Horizontal explosion underway, 19 minutes after seeding. Bottom right: Cloud has attained giant proportions. The pyrotechnic silver iodide generator (center) is one of those developed by the Naval Ordnance Test Station, China Lake, California, for the Stormfury program.

Fig. 16. Profile of the seeded cloud of Fig. 15 constructed from projecting the whole series of photographs. Scale obtained from radar pictures. (a) Above is the first phase: First, third and fourth intervals 4 minutes, second interval 5 minutes. (b) Below is the second phase: First interval, 21 minutes, second interval, 4 minutes.

Fig. 17. Calculation using cloud model on 4 km diameter clouds under mean hurricane conditions. Left: Ascent rates $w$ in meters per sec. Right: Temperature excess $\Delta T$ of cloud over surroundings, in $^{o}C$. Solid curves denote unfrozen cloud. Dotted curves denote cloud naturally freezing its water between $-15^{o}C$ and $-30^{o}C$. Dashed and x-ed curves denote seeded cloud, with water frozen between $-4^{o}C$ and $-8^{o}C$. Dashed curve adds fusion heat only. X-ed curve also expands the tower by one-third and, after seeding, precipitates three-quarters of the condensate.

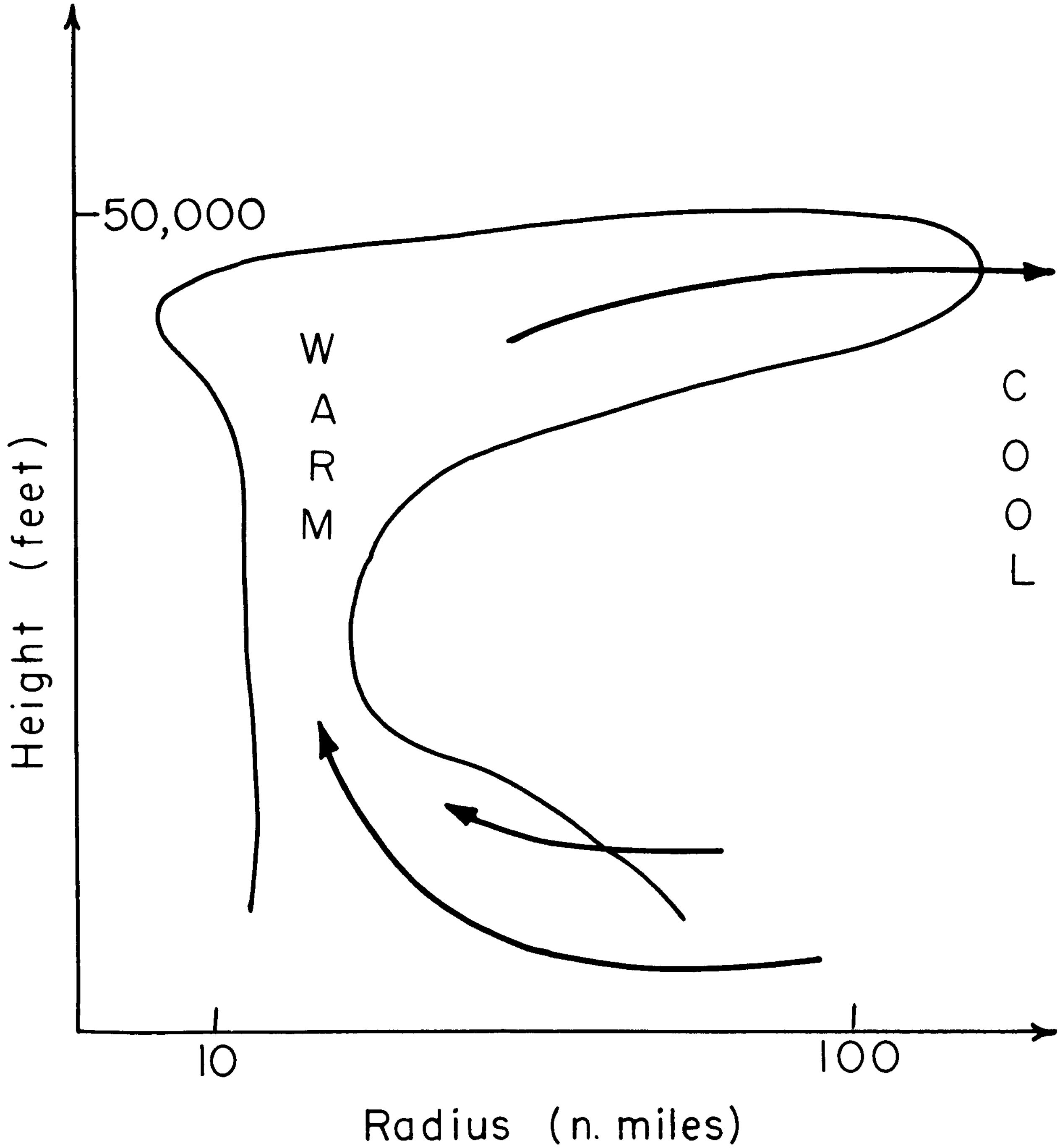



Fig. 1a

Horizontal View: Inflow

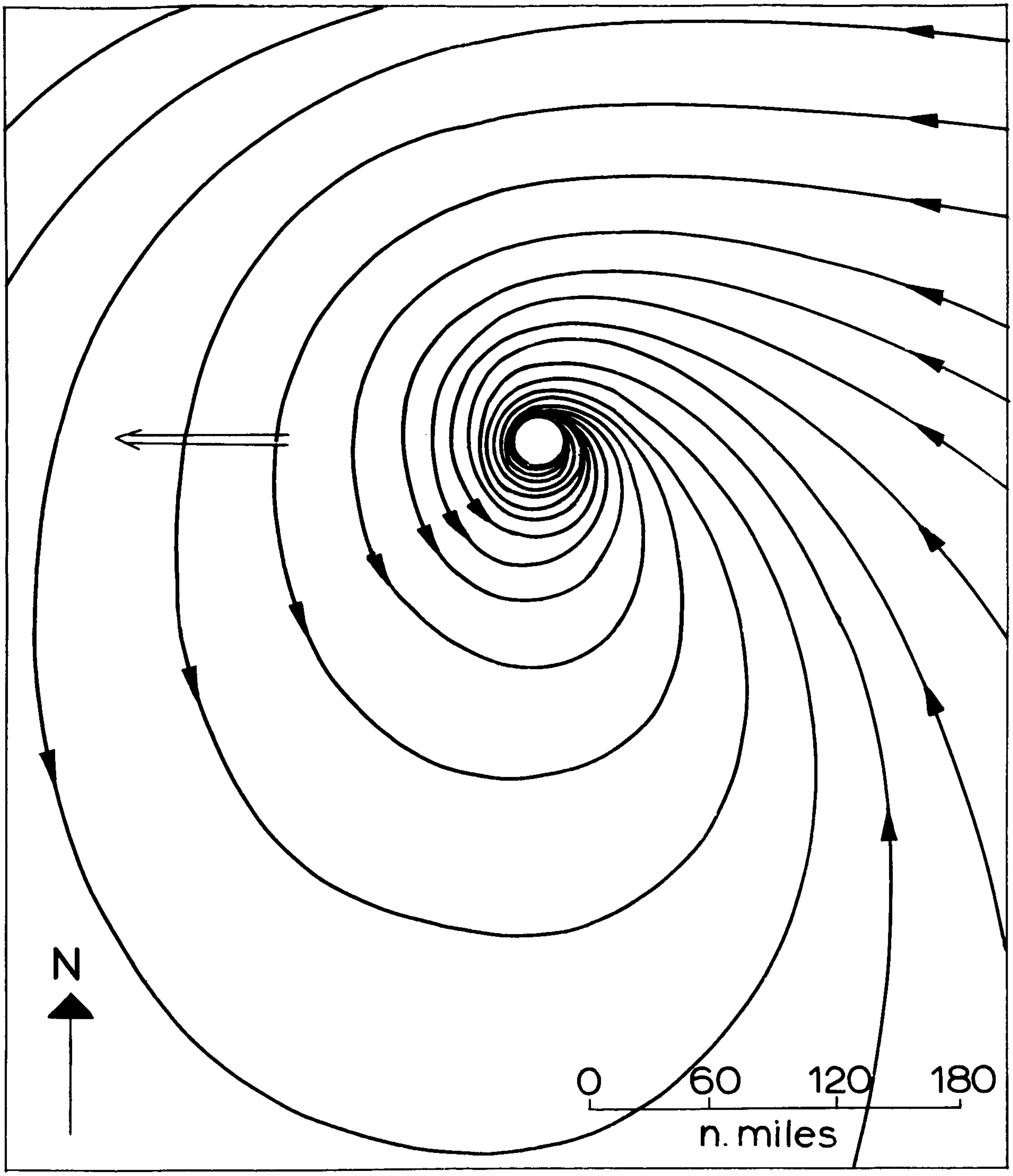



Fig. 1b

Horizontal View: Outflow

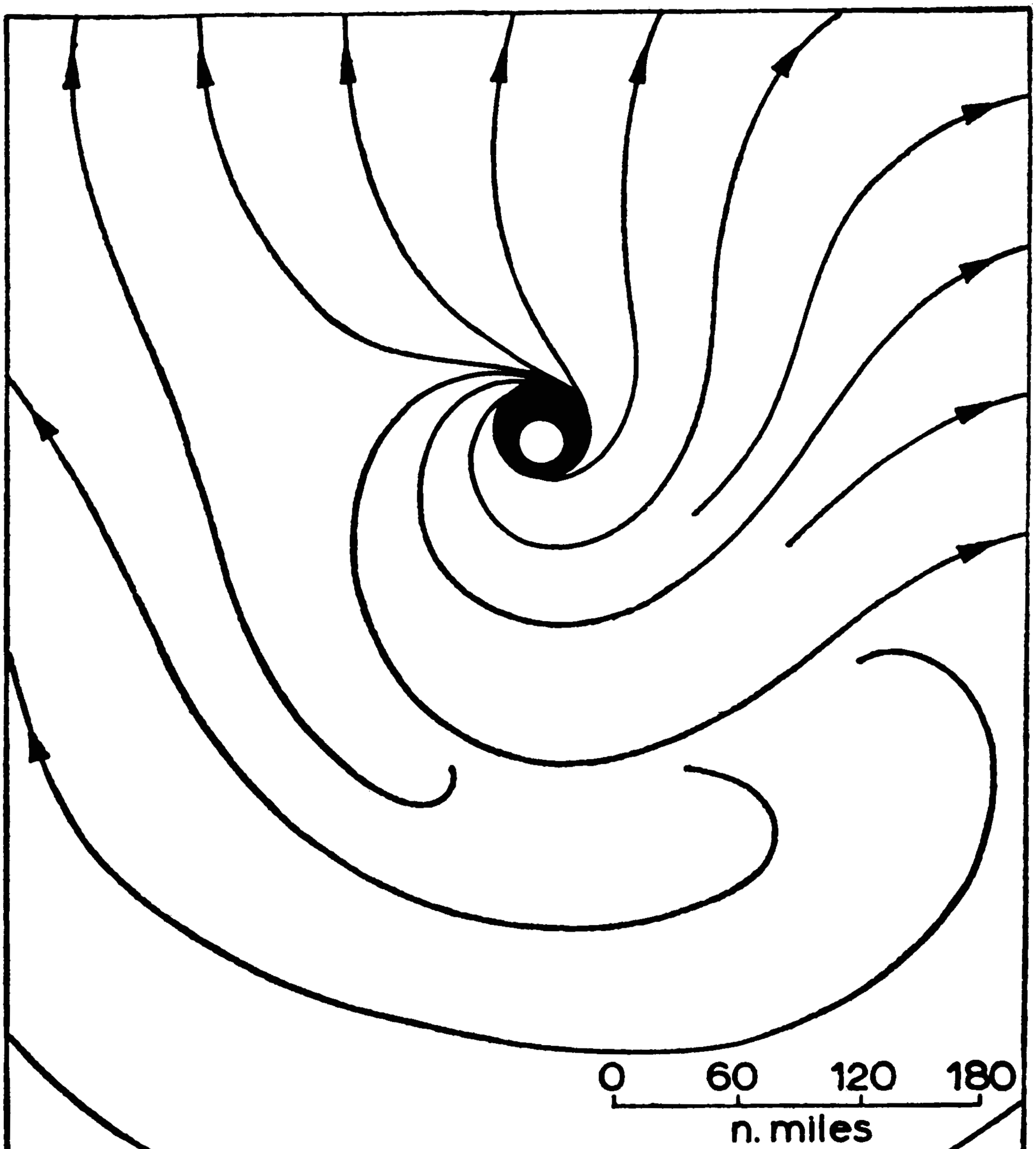



Fig. 1c

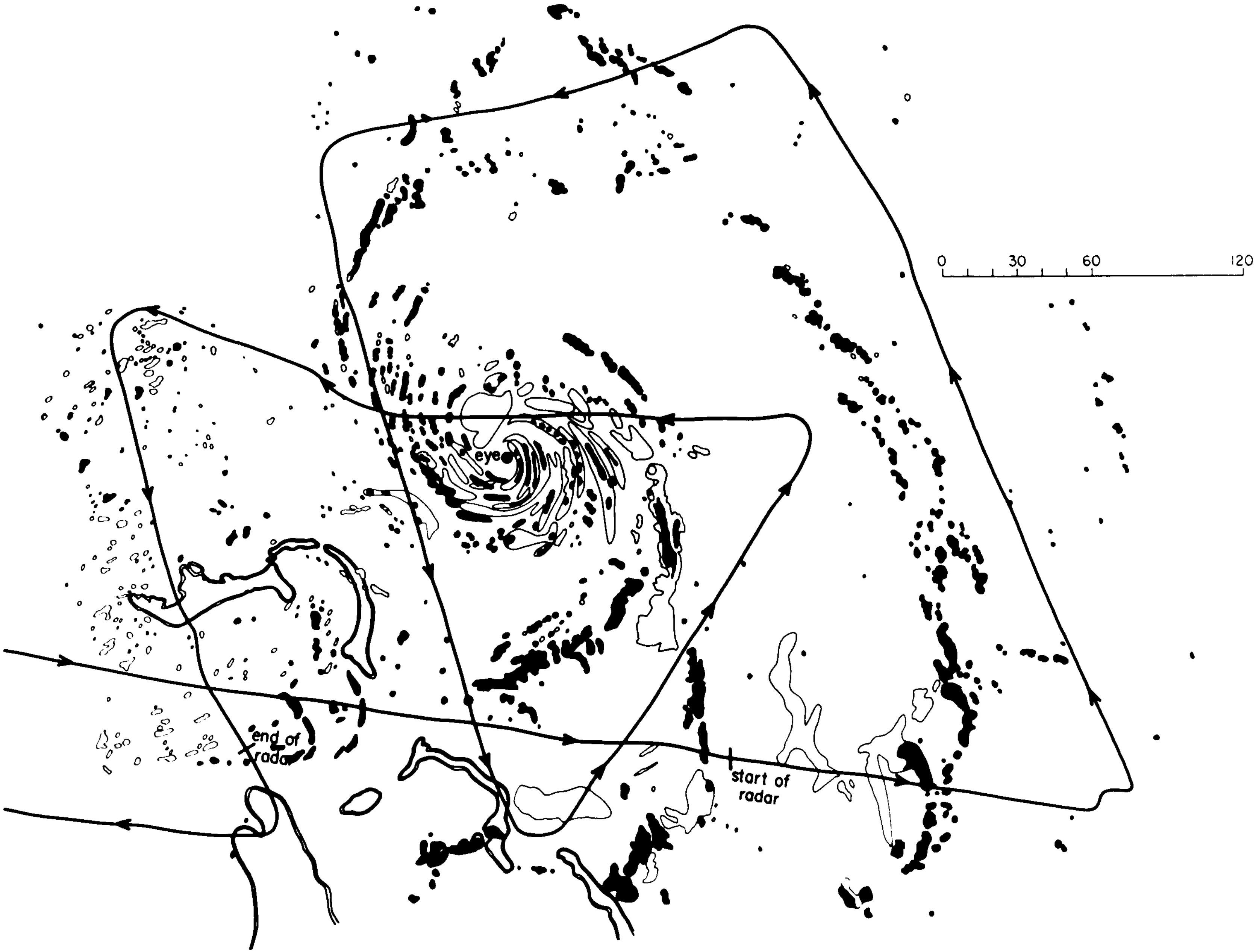
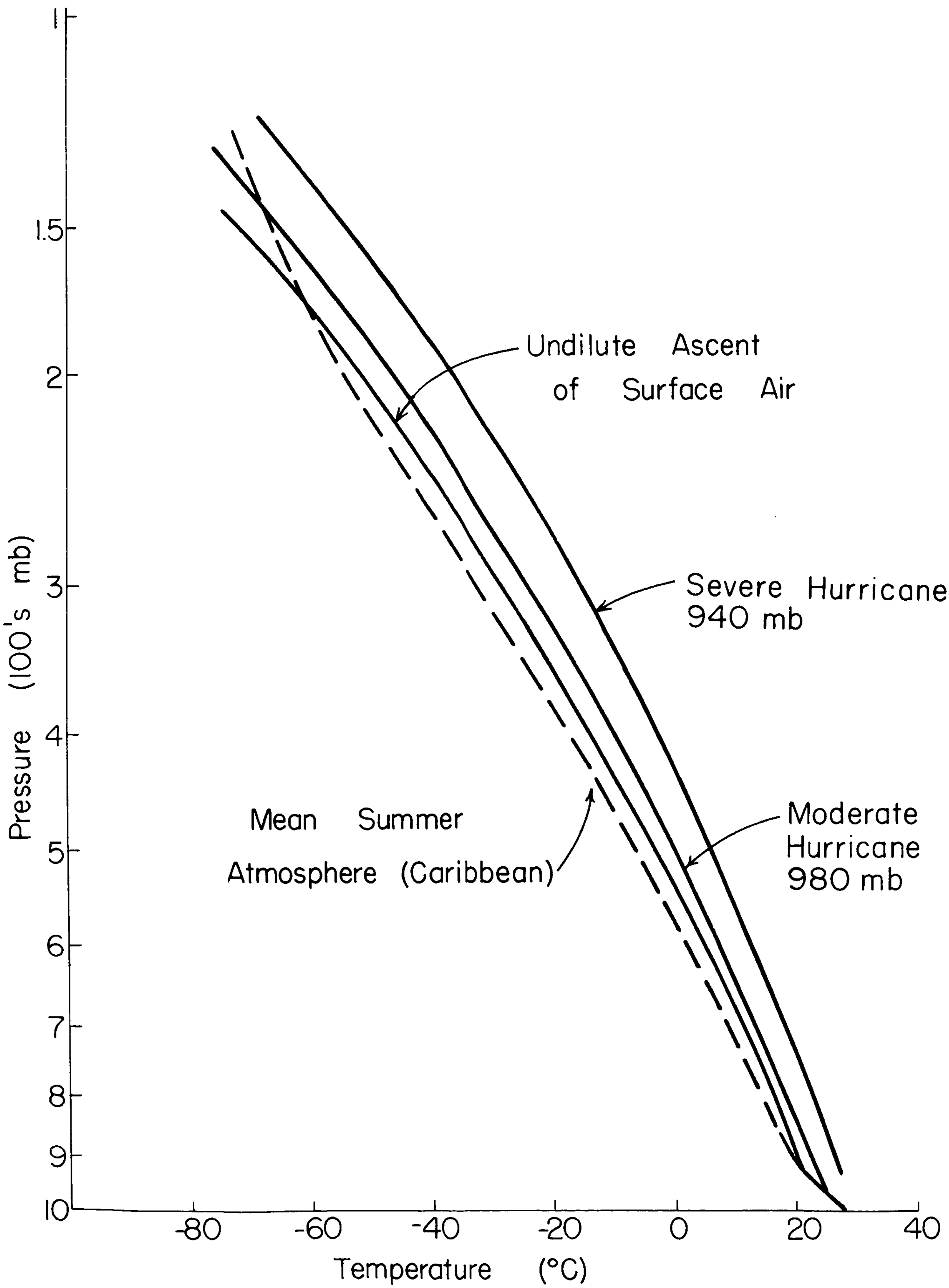
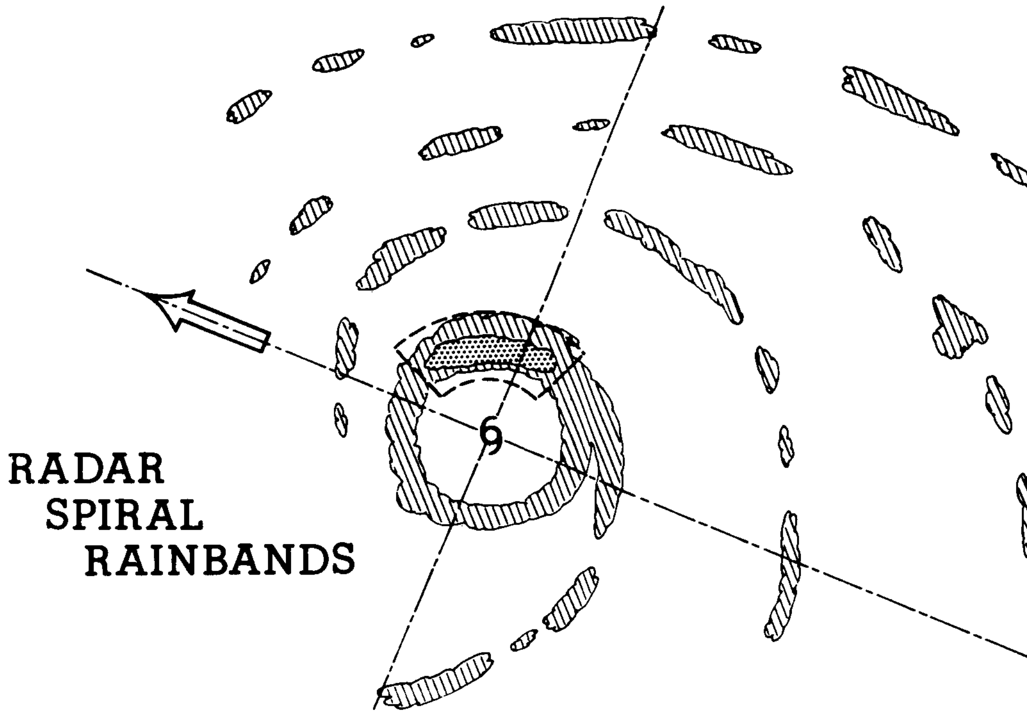



Fig. 2



Undilute Ascent of Surface Air
Severe Hurricane 940 mb
Moderate Hurricane 980 mb
Mean Summer Atmosphere (Caribbean)
Pressure (100's mb)
1
1.5
2
3
4
5
6
7
8
9
10
-80
-60
-40
-20
0
20
40
Temperature (°C)


Fig. 3




HURRICANE MODEL

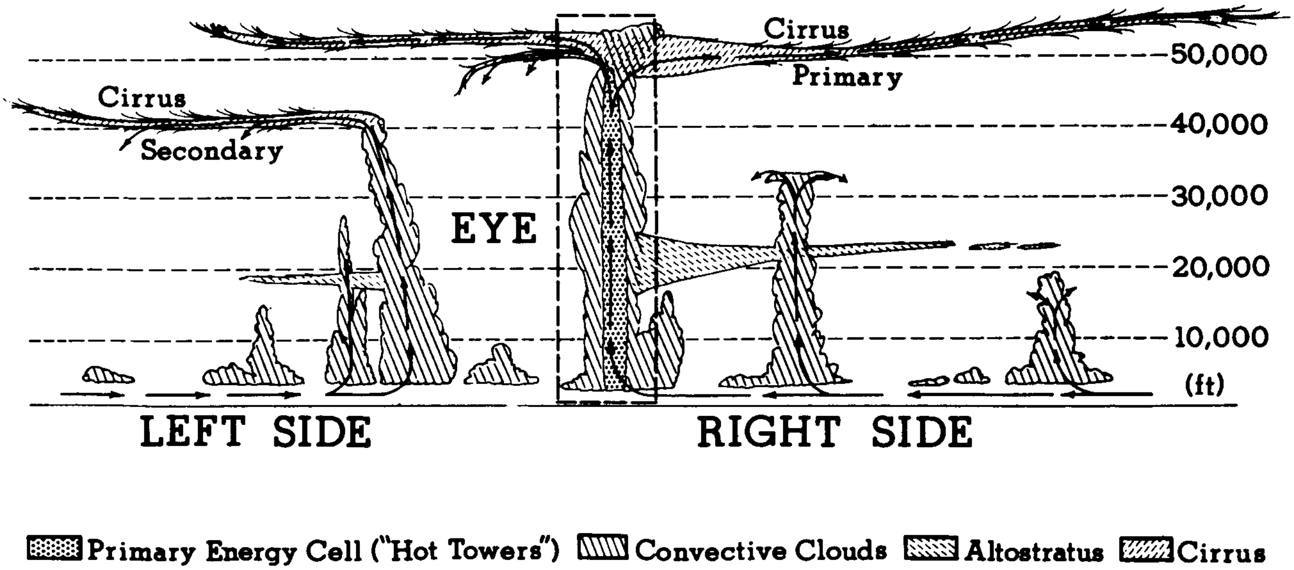



Fig. 4

## PARCEL ASCENT OF SUBCLOUD AIR IN THE HURRICANE

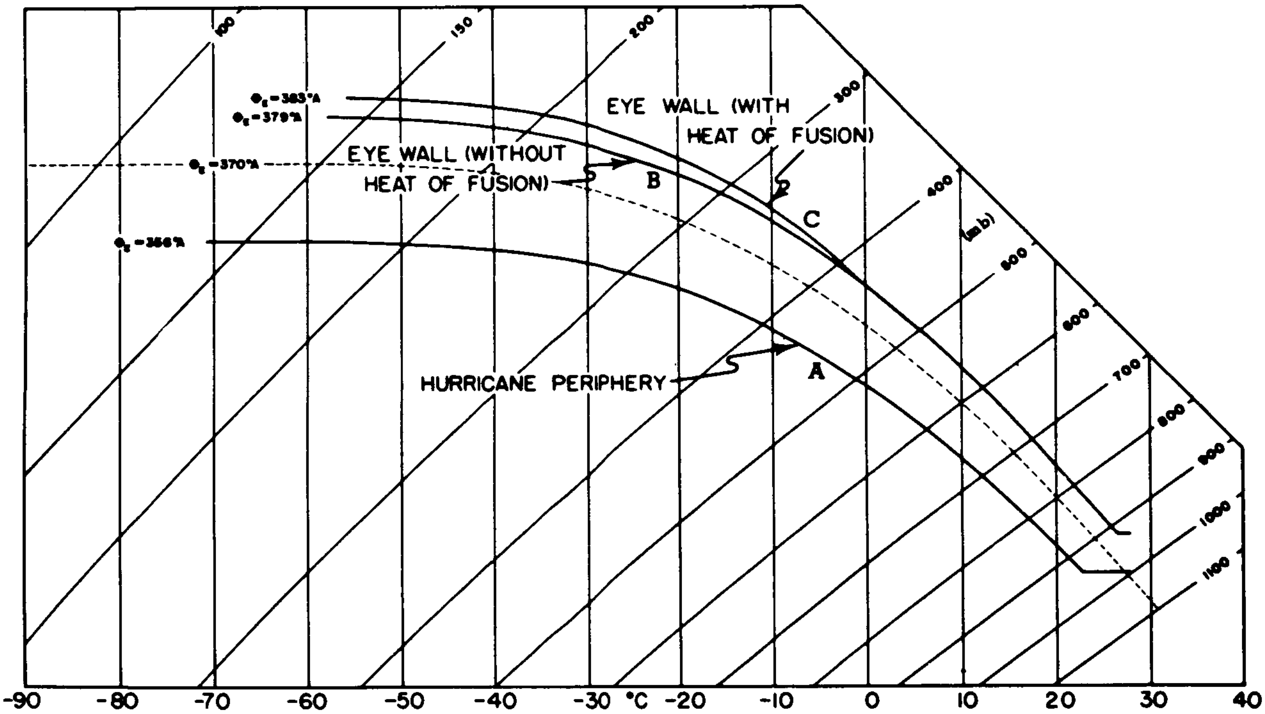



Fig. 5

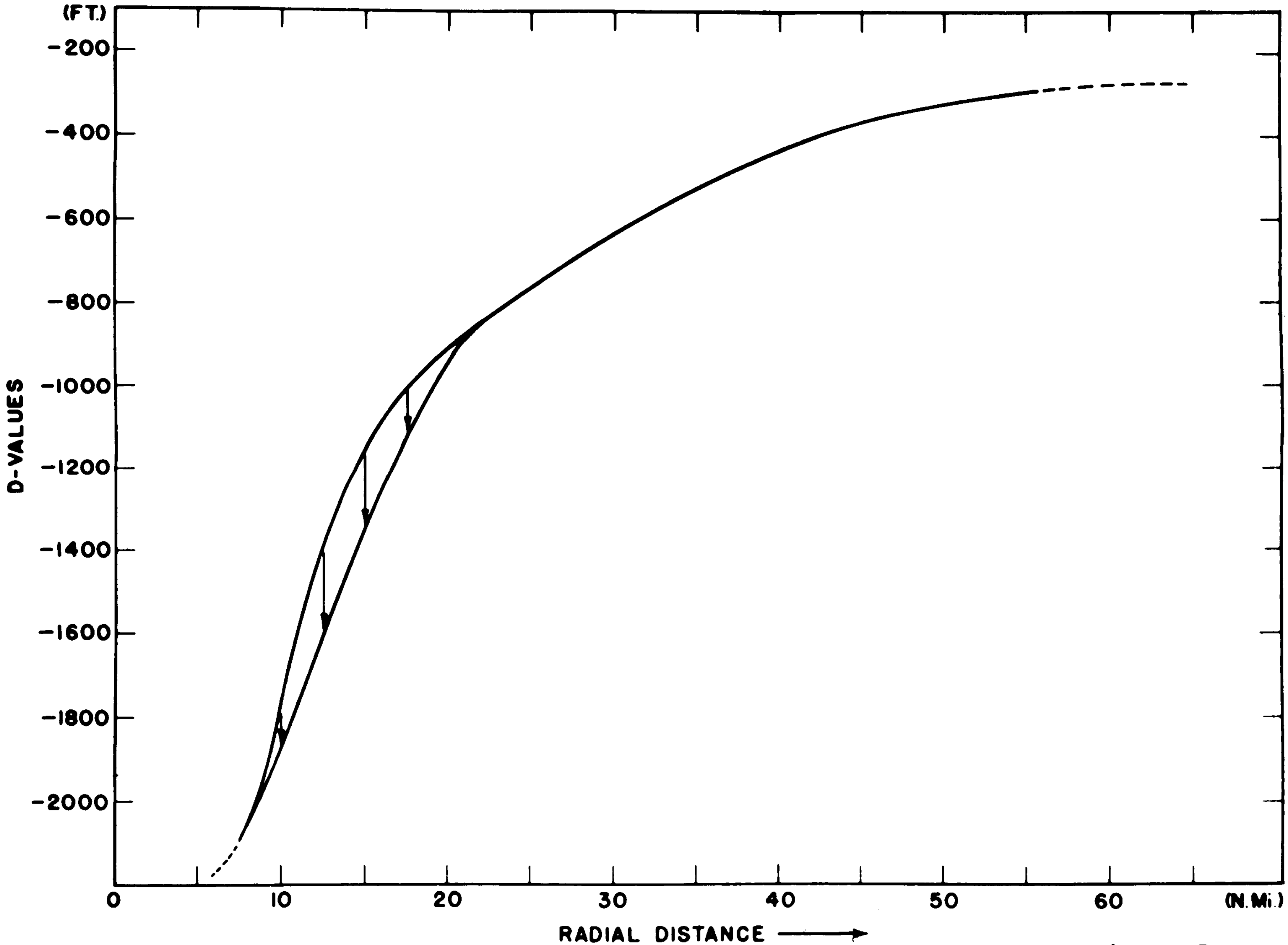
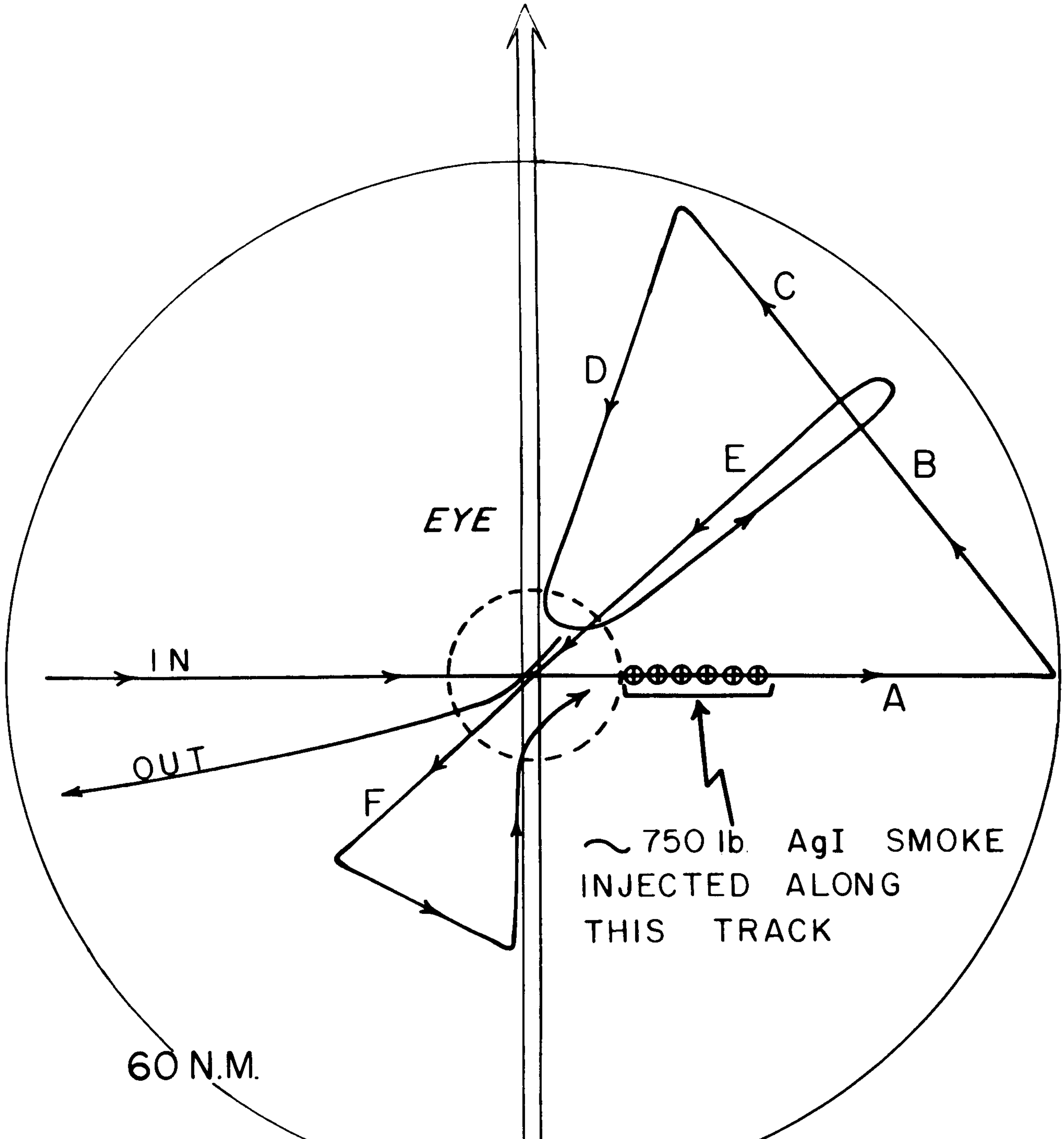

(FT.)
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
D-VALUES
0
10
20
30
40
50
60
(N.Mi.)
RADIAL DISTANCE

Fig. 6



C
D
E
B
EYE
IN
A
OUT
F
~ 750 lb. AgI SMOKE
INJECTED ALONG
THIS TRACK
60 N.M.


Fig. 7

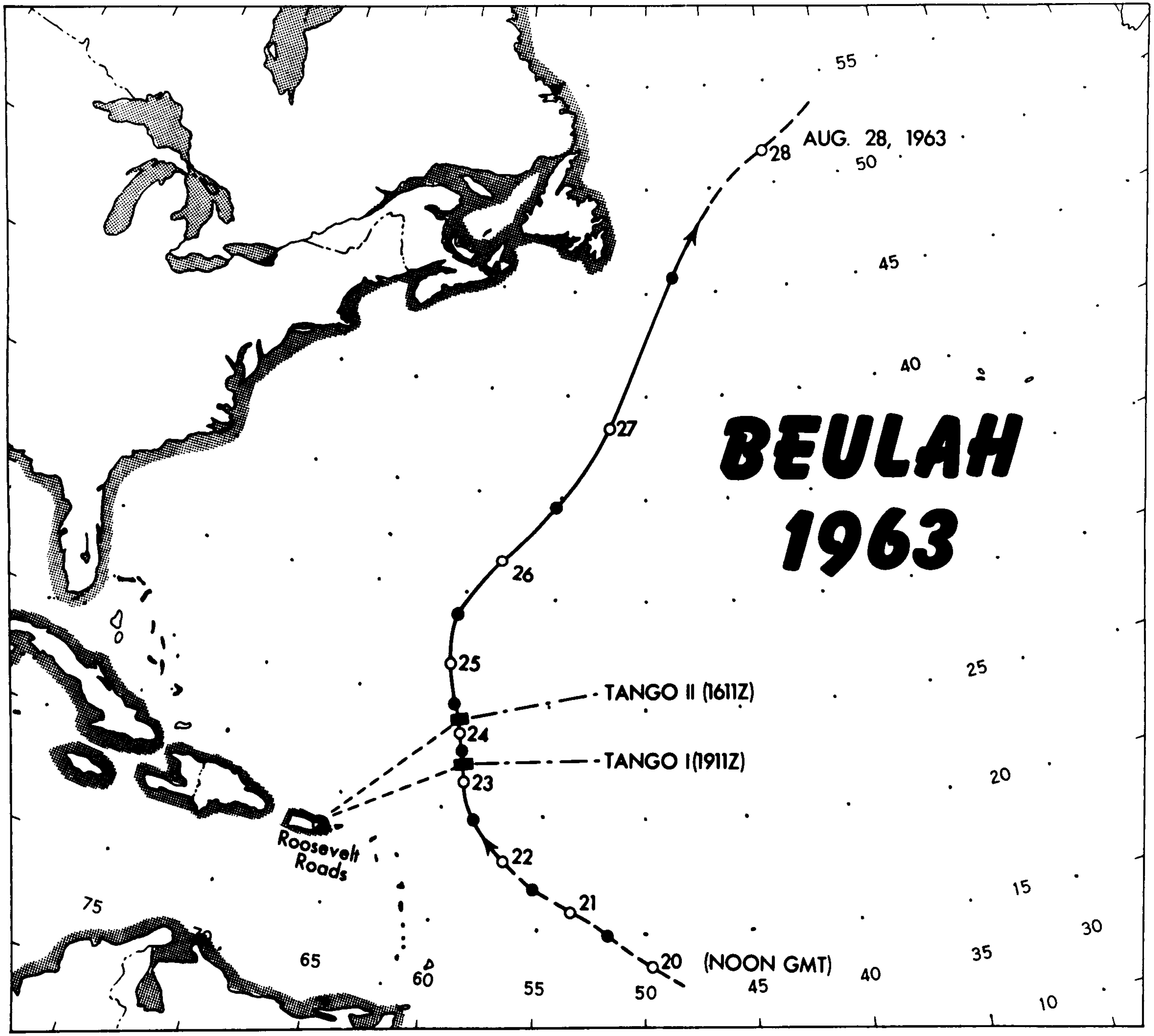

BEULAH
1963
AUG. 28, 1963
28
27
26
25
24
23
22
21
20
(NOON GMT)
TANGO II (1611Z)
TANGO I (1911Z)
Roosevelt Roads
55
50
45
40
25
20
15
10
30
35
40
45
50
55
60
65
75

Fig. 8

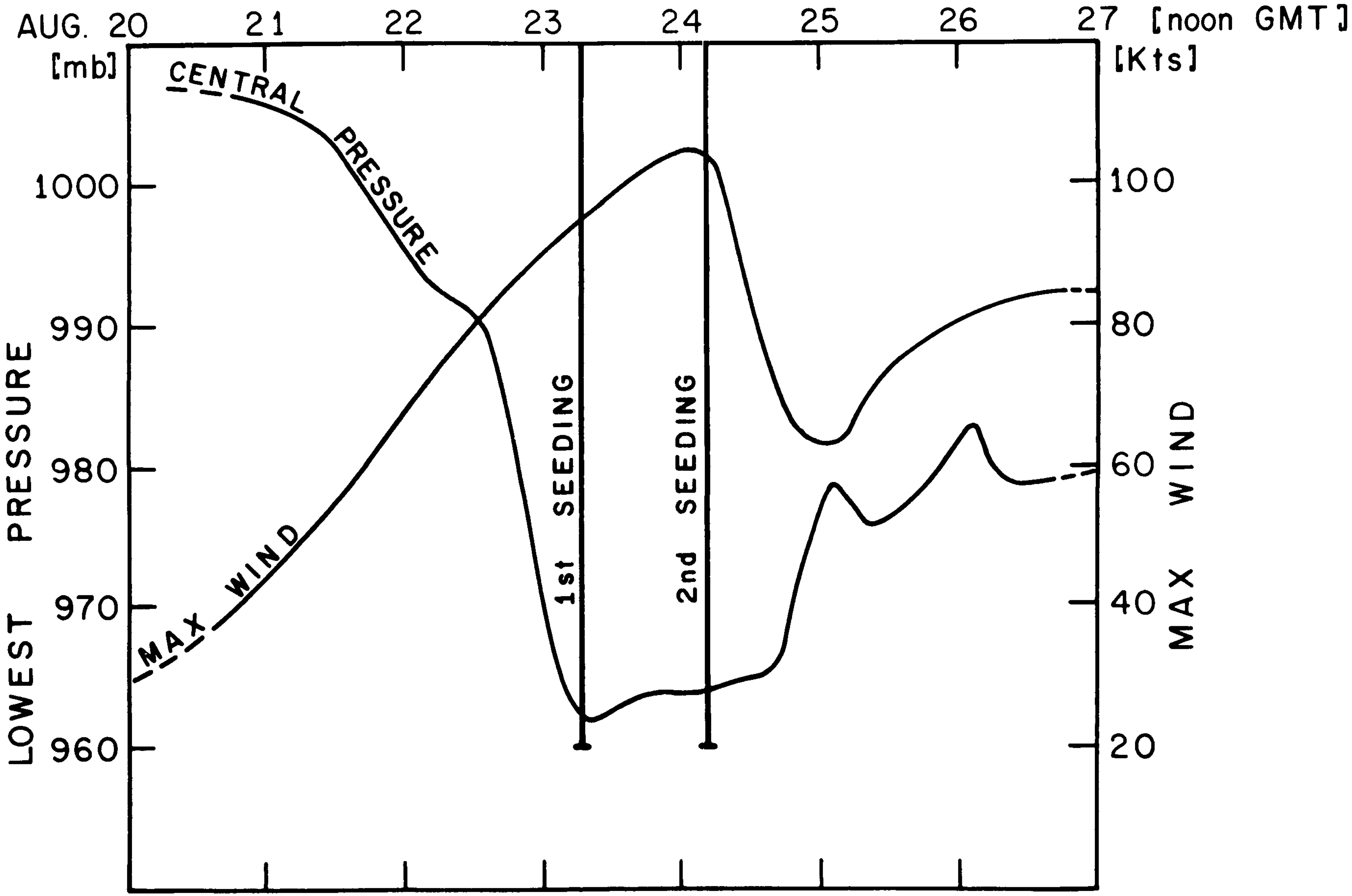
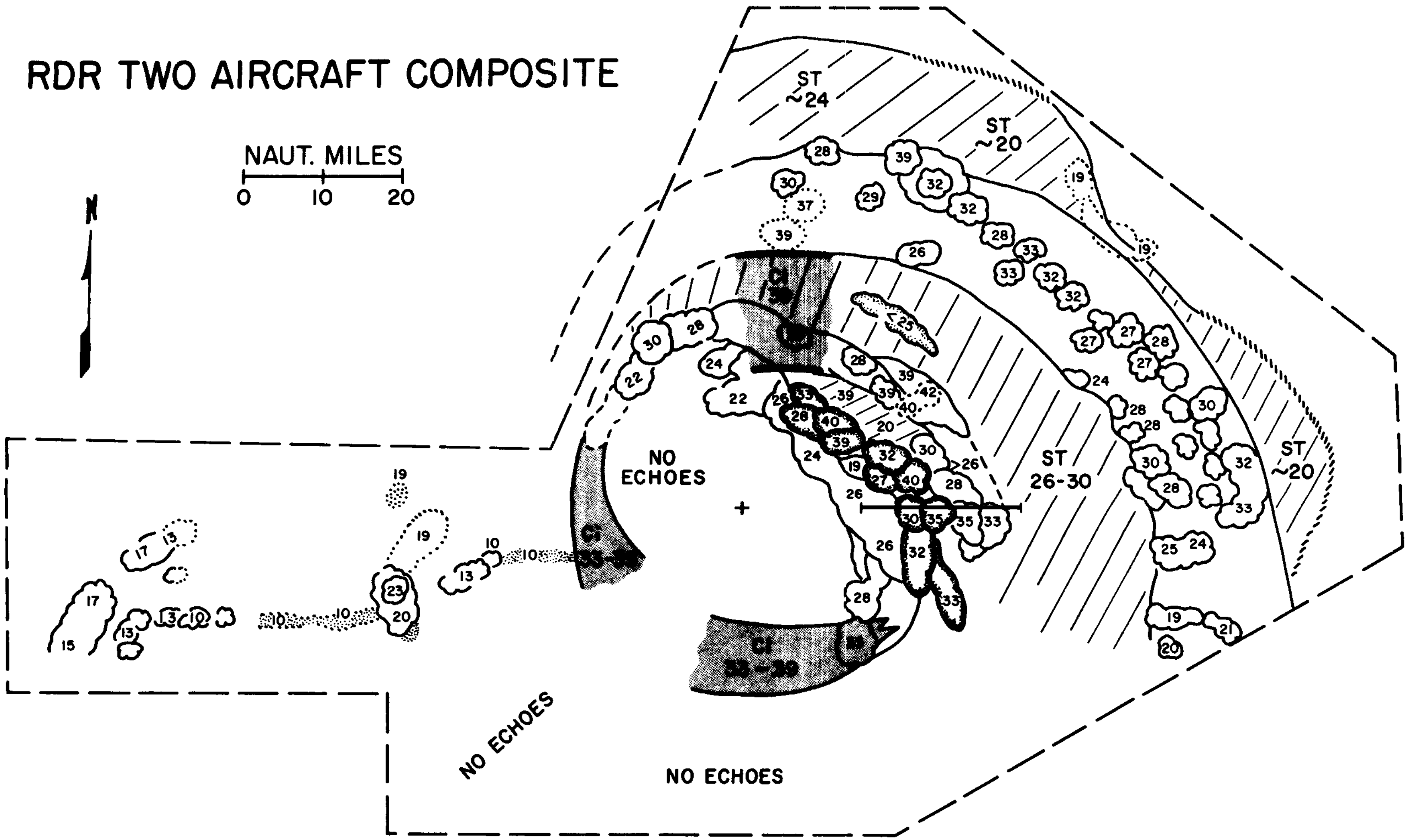

AUG. 20
21
22
23
24
25
26
27 [noon GMT]
[mb]
[Kts]
CENTRAL PRESSURE
MAX WIND
1000
990
980
970
960
LOWEST PRESSURE
100
80
60
40
20
MAX WIND
1st SEEDING
2nd SEEDING
BEULAH

Fig. 9

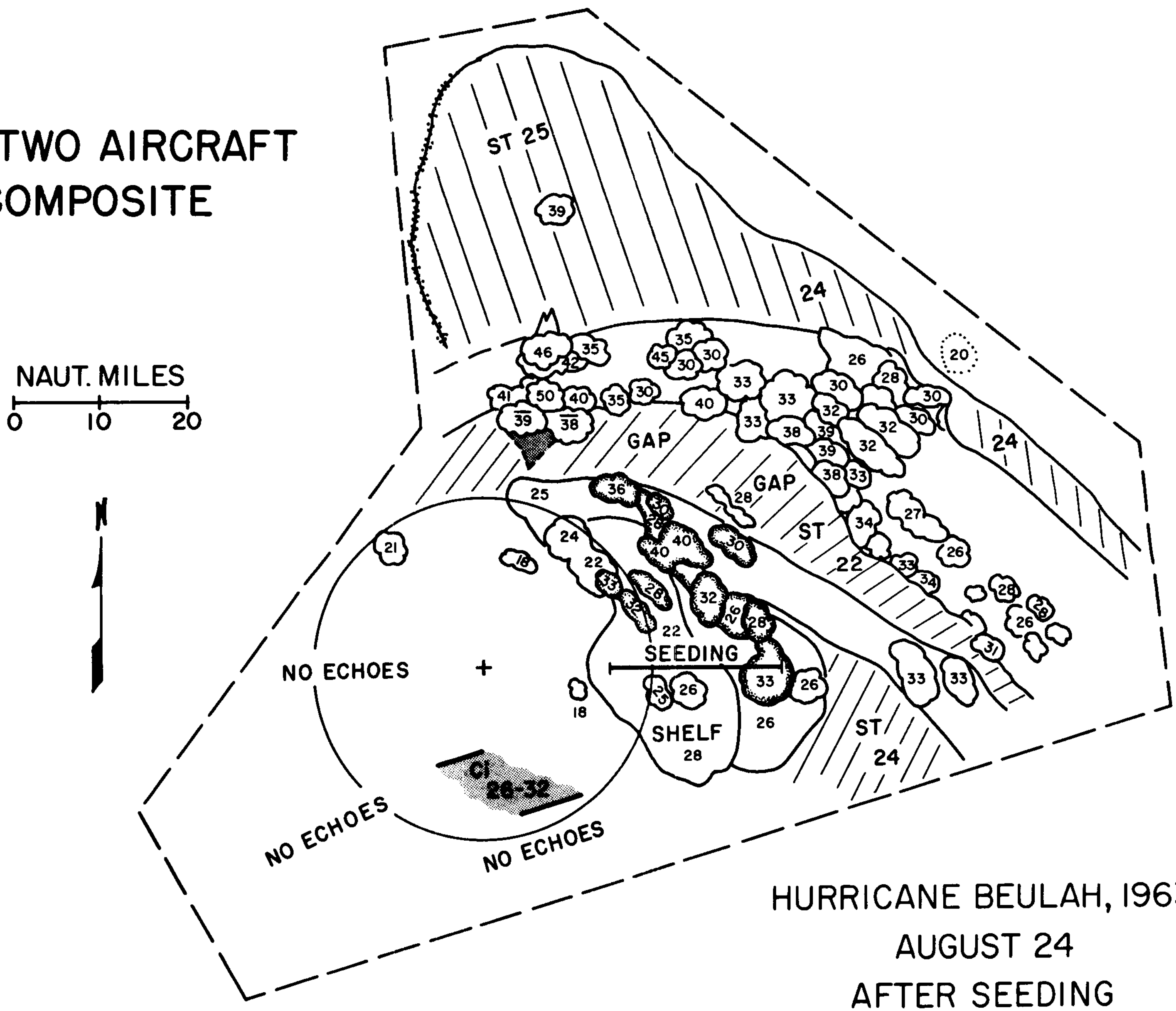
RDR TWO AIRCRAFT COMPOSITE




HURRICANE BEULAH, 1963
AUGUST 24
BEFORE SEEDING
1350-1611 Z

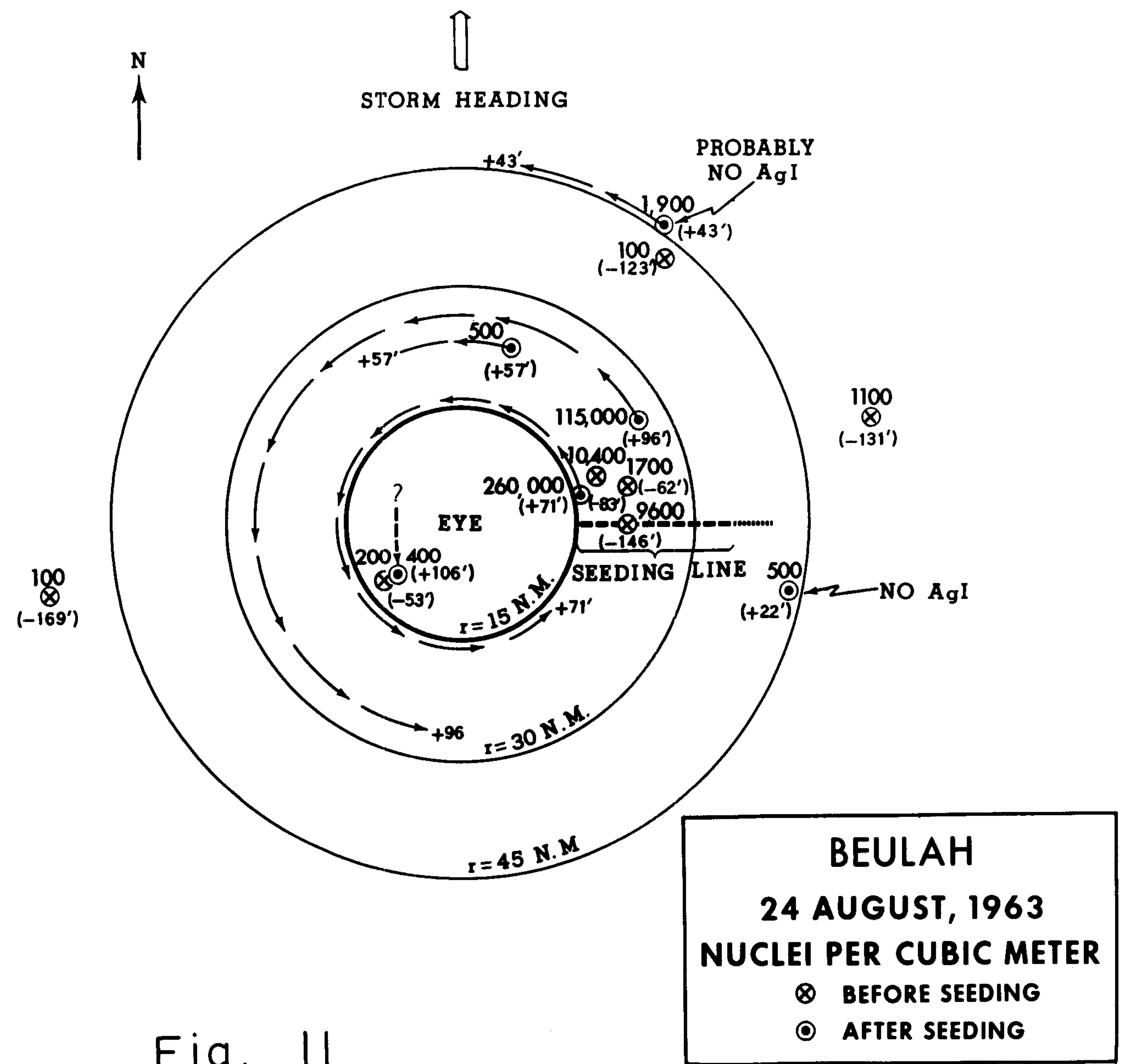
Fig. 10 a

RDR TWO AIRCRAFT
COMPOSITE




HURRICANE BEULAH, 1963
AUGUST 24
AFTER SEEDING
1611-1820 Z

Fig. 10 b



N
STORM HEADING
PROBABLY
NO AgI
+43'
1,900
(+43')
100
(-123')
500
(+57')
+57'
115,000
(+96')
10,400
1700
(-62')
260,000
(+71')
(-83')
9600
(-146')
?
EYE
200
400
(+106')
(-53')
SEEDING LINE
500
(+22')
NO AgI
1100
(-131')
100
(-169')
r=15 N.M.
+71'
+96
r=30 N.M.
r=45 N.M.
BEULAH
24 AUGUST, 1963
NUCLEI PER CUBIC METER
BEFORE SEEDING
AFTER SEEDING


Fig. 11

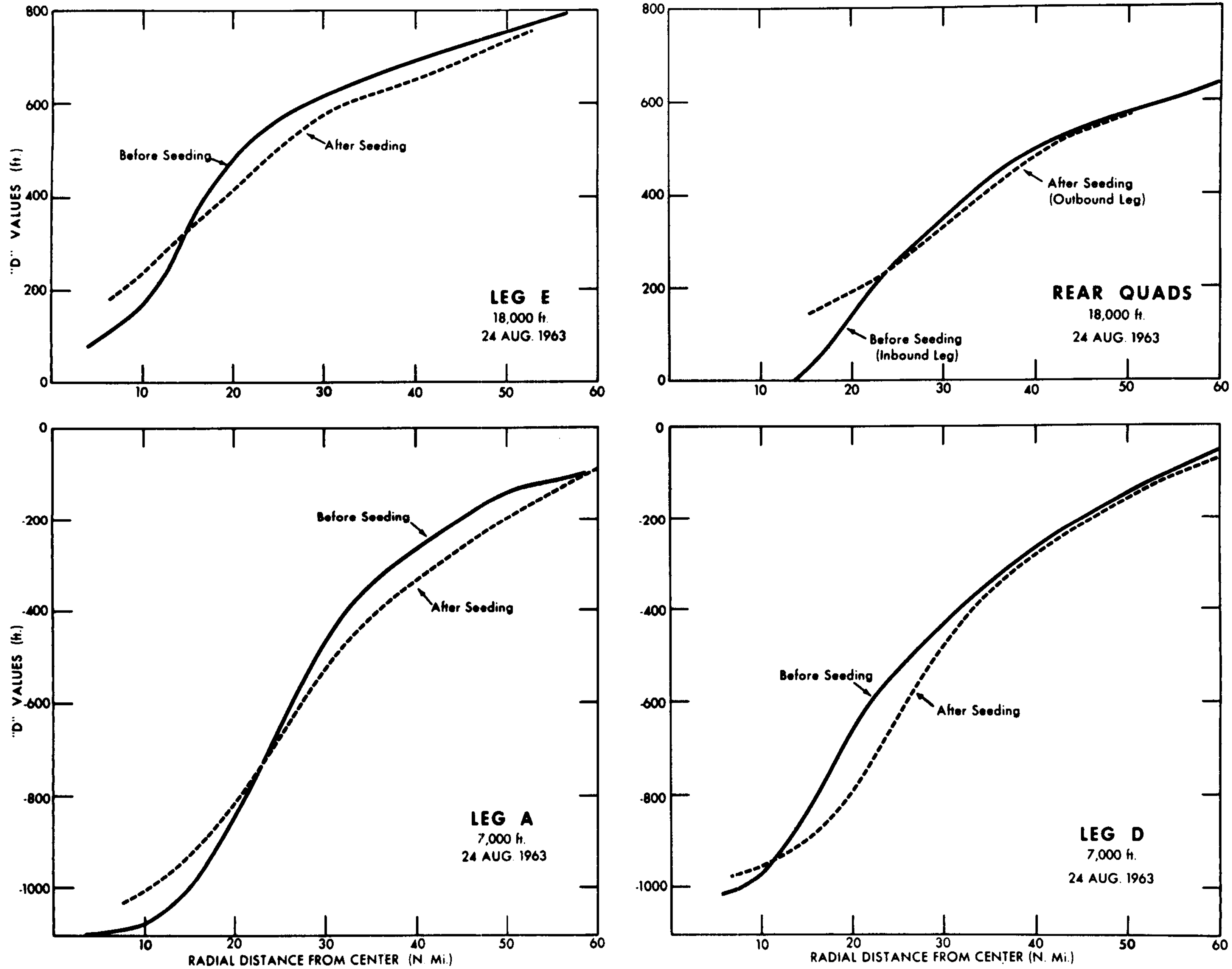

"D" VALUES (ft.)
Before Seeding
After Seeding
LEG E
18,000 ft.
24 AUG. 1963
After Seeding
(Outbound Leg)
Before Seeding
(Inbound Leg)
REAR QUADS
18,000 ft.
24 AUG. 1963
Before Seeding
After Seeding
LEG A
7,000 ft.
24 AUG. 1963
Before Seeding
After Seeding
LEG D
7,000 ft.
24 AUG. 1963
RADIAL DISTANCE FROM CENTER (N. Mi.)

Fig. 12

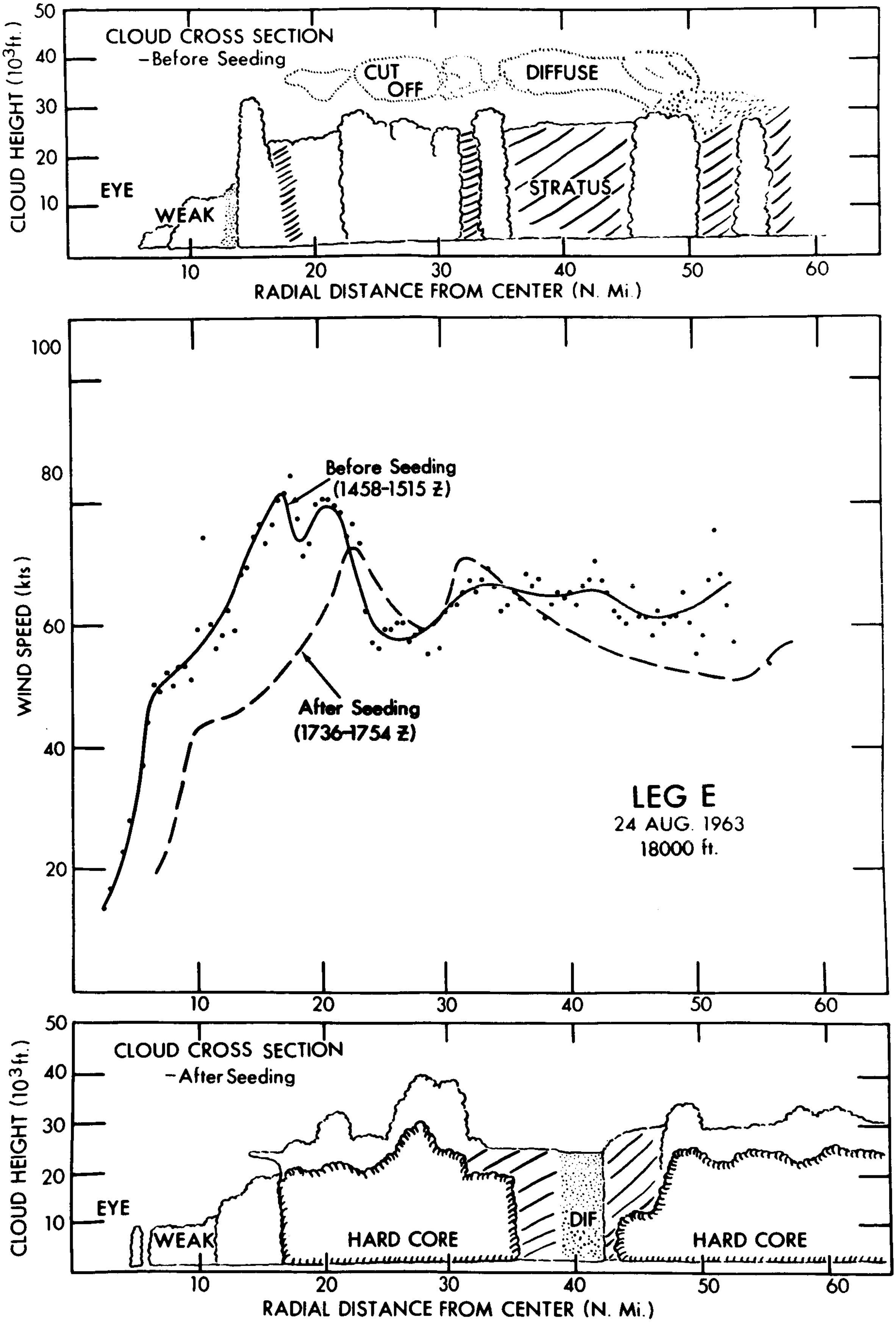

CLOUD CROSS SECTION
-Before Seeding
CUT OFF
DIFFUSE
EYE
WEAK
STRATUS
CLOUD HEIGHT (10³ft.)
RADIAL DISTANCE FROM CENTER (N. Mi.)
Before Seeding
(1458-1515 Z)
After Seeding
(1736-1754 Z)
LEG E
24 AUG. 1963
18000 ft.
WIND SPEED (kts)
CLOUD CROSS SECTION
-After Seeding
EYE
WEAK
HARD CORE
DIF
HARD CORE
CLOUD HEIGHT (10³ft.)
RADIAL DISTANCE FROM CENTER (N. Mi.)

Fig. 13

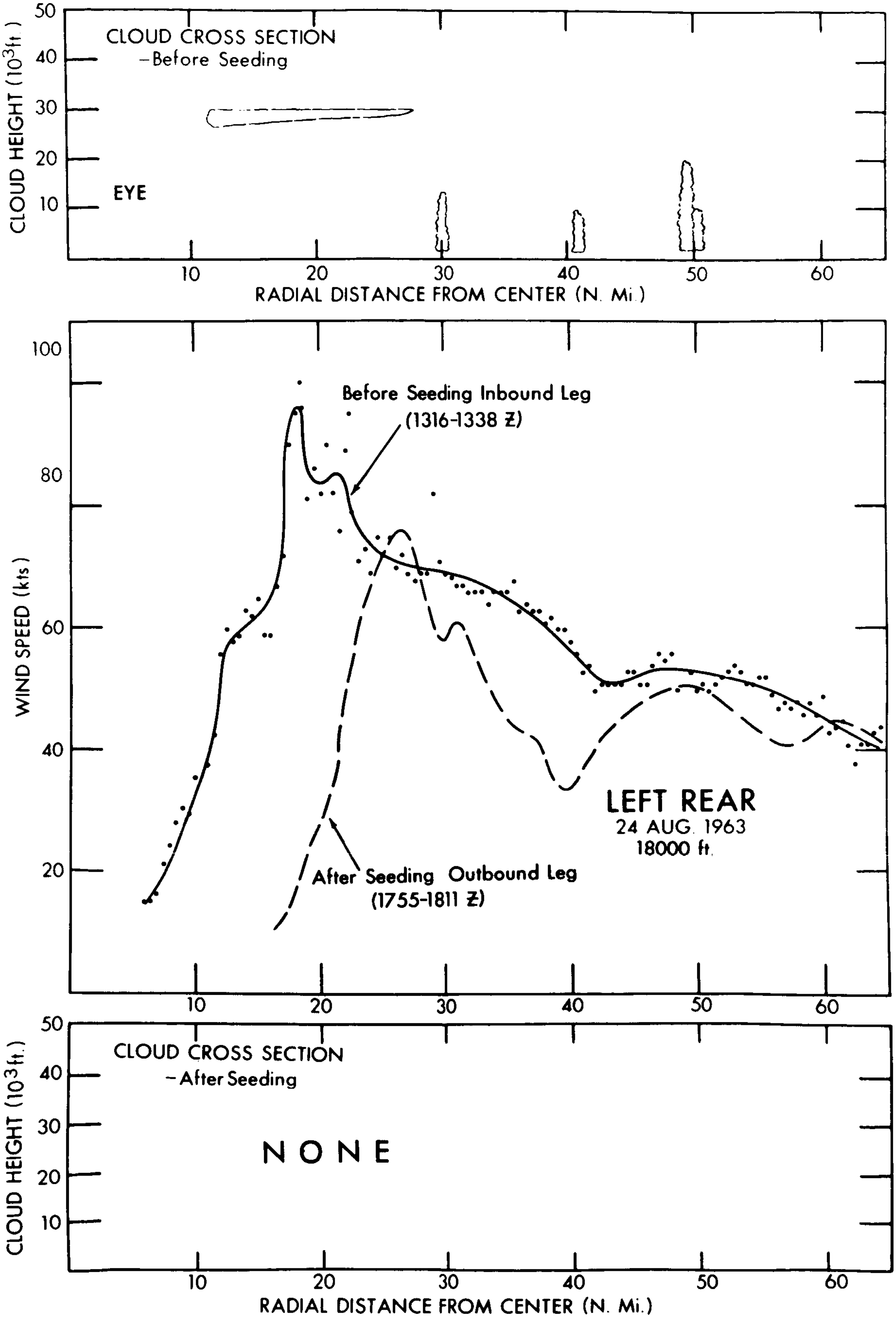

CLOUD CROSS SECTION
–Before Seeding
EYE
CLOUD HEIGHT ($10^3$ft.)
RADIAL DISTANCE FROM CENTER (N. Mi.)
Before Seeding Inbound Leg
(1316-1338 Z)
After Seeding Outbound Leg
(1755-1811 Z)
LEFT REAR
24 AUG. 1963
18000 ft.
WIND SPEED (kts)
CLOUD CROSS SECTION
–After Seeding
NONE
CLOUD HEIGHT ($10^3$ft.)
RADIAL DISTANCE FROM CENTER (N. Mi.)

Fig. 14

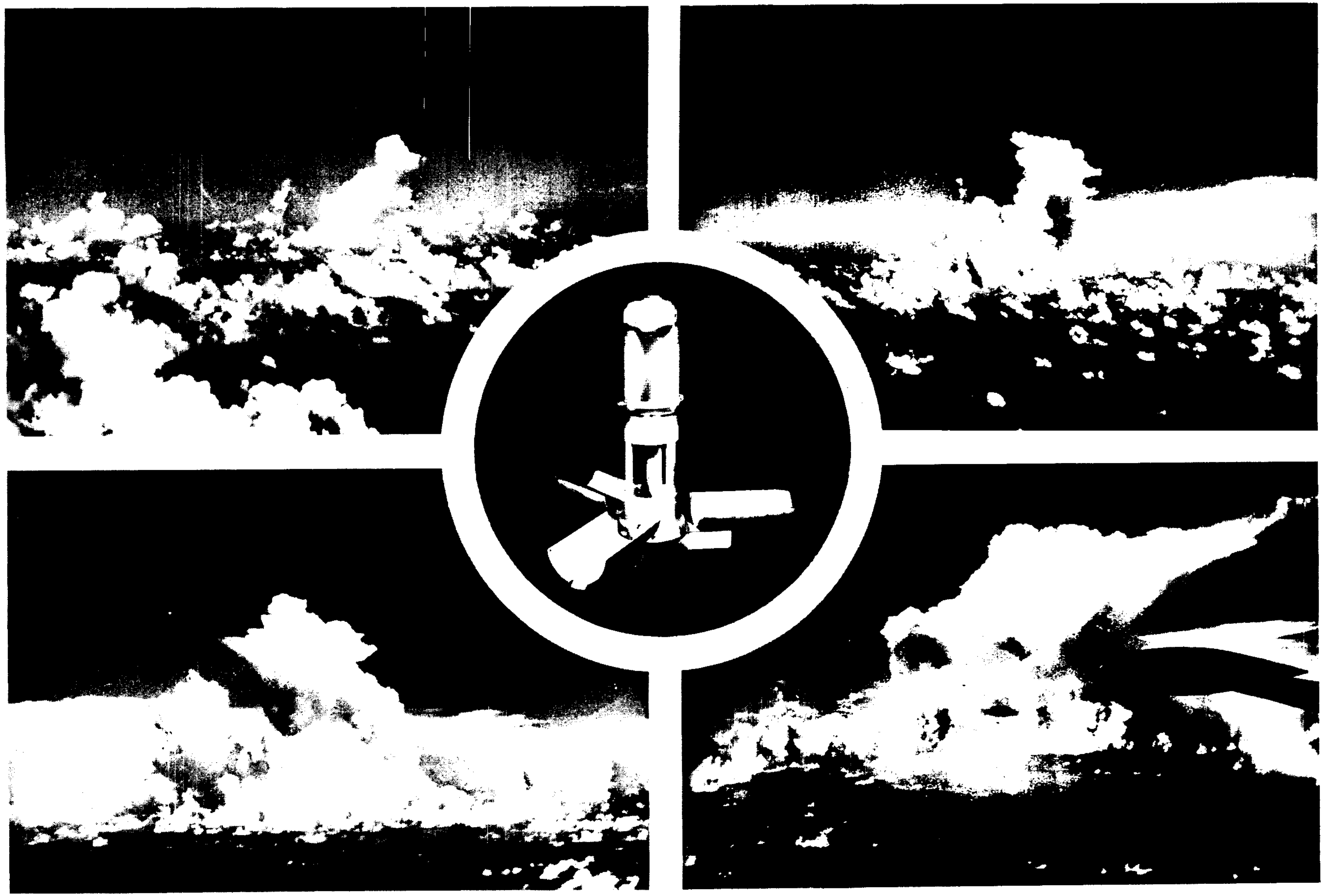
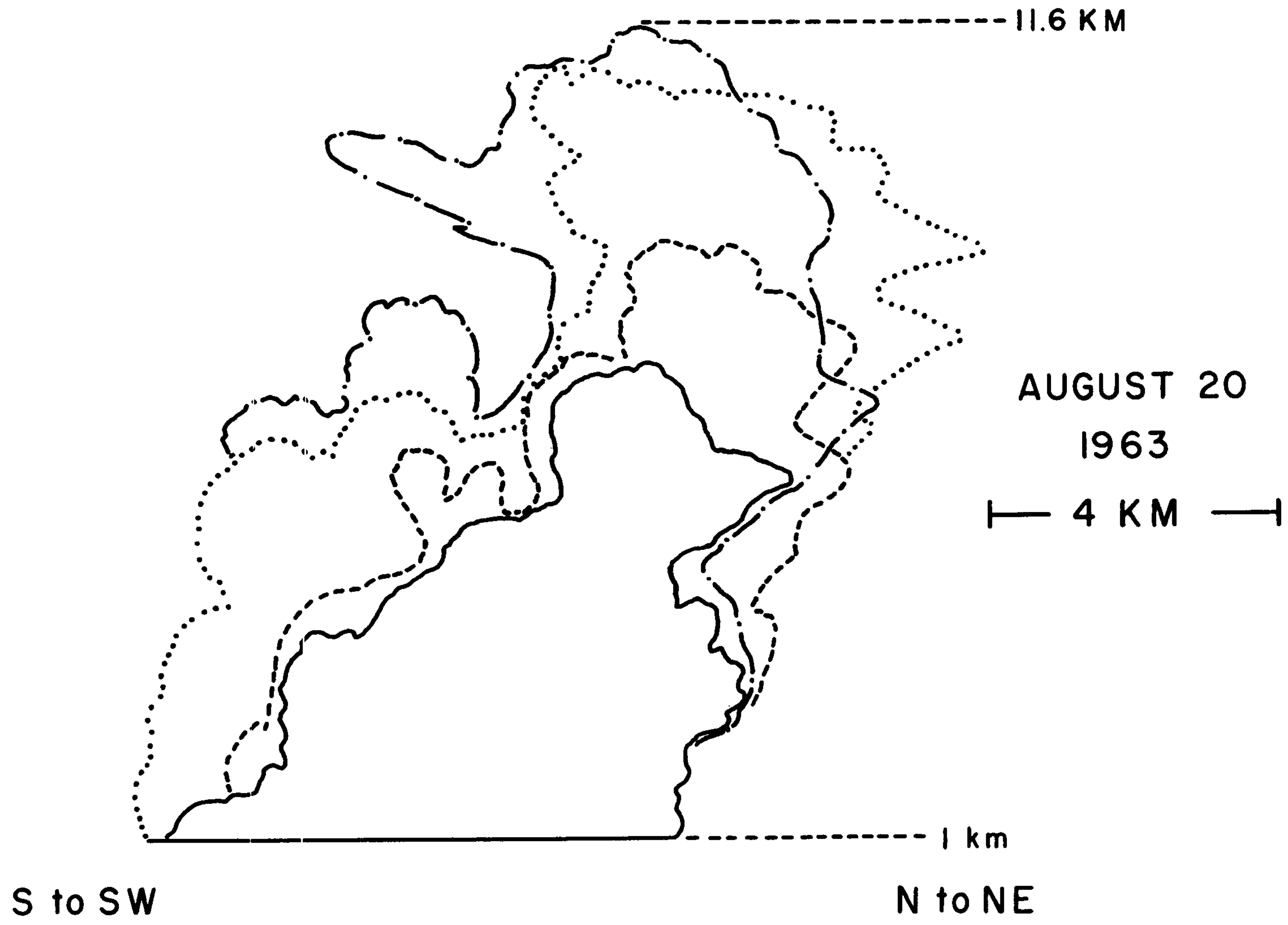
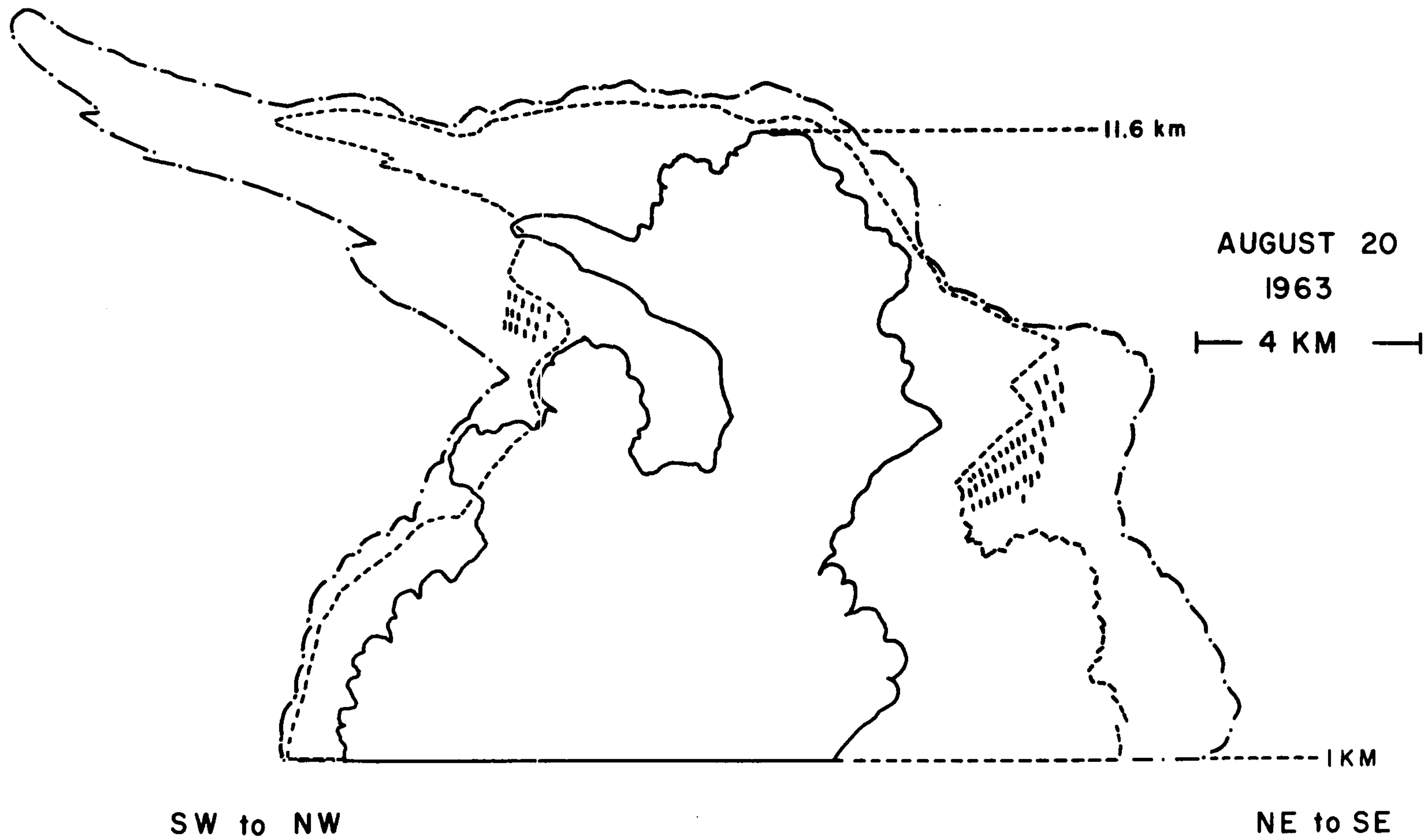


Fig. 15



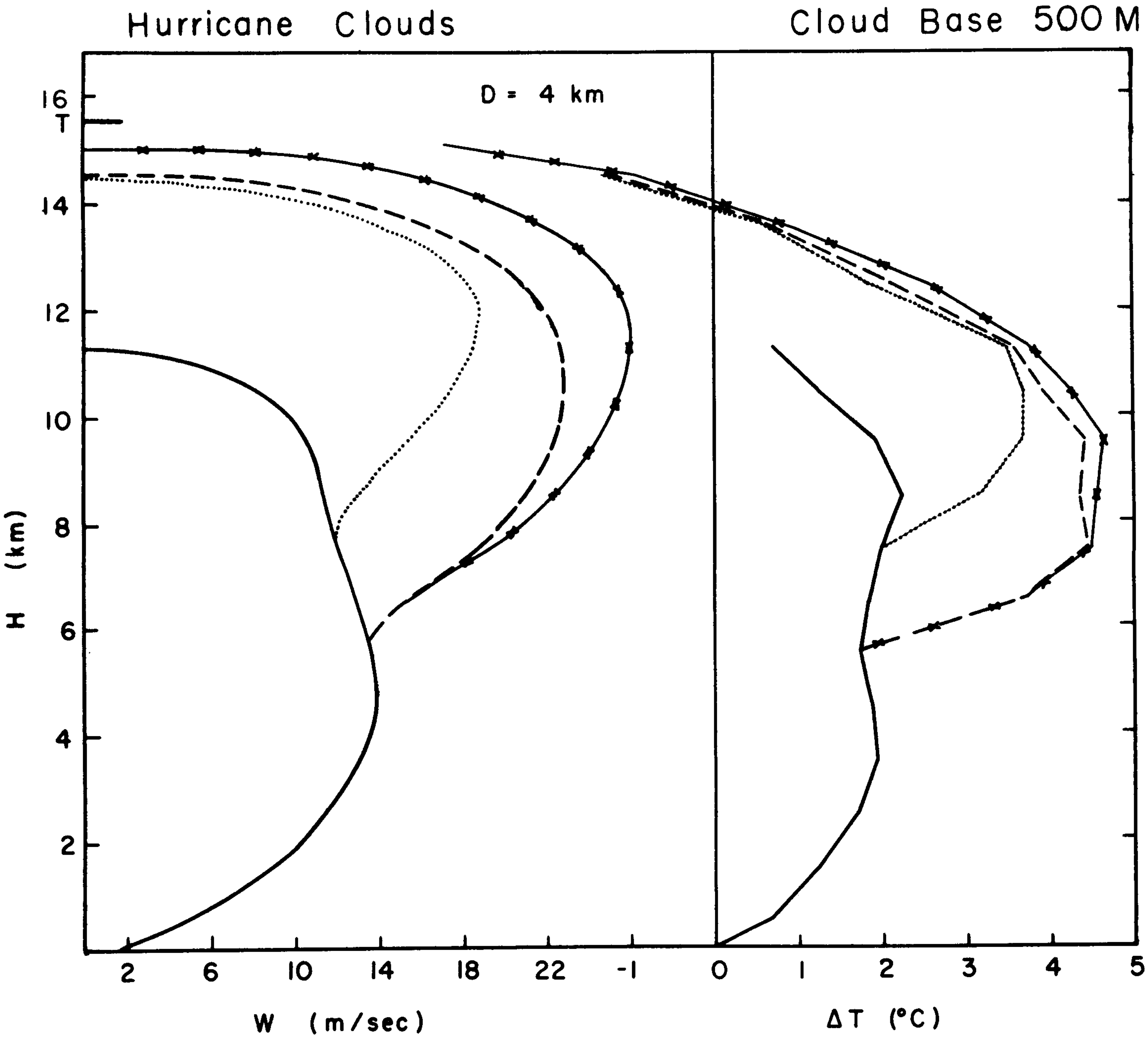

"EXPLOSION"
FIRST PHASE

Fig. 16a




"EXPLOSION"
SECOND PHASE

Fig. 16 b



Hurricane Clouds
Cloud Base 500 M
D = 4 km
H (km)
16
T
14
12
10
8
6
4
2
2
6
10
14
18
22
-1
0
1
2
3
4
5
W (m/sec)
ΔT (°C)


Fig. 17